EVALUATION OF BIOMECHANICAL RISK FACTORS IN DIVISION II COLLEGIATE FEMALE ATHLETES USING THE LANDING ERROR SCORING SYSTEM (LESS) AFTER AN 8-WEEK NEUROMUSCULAR TRAINING PROGRAM

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Title

Evaluation of Biomechanical Risk Factors in Division II Collegiate Female Athletes Using the Landing Error Scoring System (LESS) After an 8-Week Neuromuscular Training Program

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MASTER OF SCIENCE

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ABSTRACT

Neuromuscular training programs are a relatively new injury prevention strategy to reduce the risk of anterior cruciate ligament (ACL) injuries, primarily in female athletes. This study evaluated the effects of a neuromuscular training program on Landing Error Scoring System (LESS) scores, maximum knee flexion, and maximum knee valgus before, during (2 wks, 4 wks, 6 wks), and after an 8-week neuromuscular training program. An 8-week neuromuscular training program significantly decreased the maximum knee valgus in female athletes but did not decrease LESS scores or increase maximum knee flexion. The findings may enhance athletic trainers' understanding of the benefits that neuromuscular training programs may provide and help clinicians make decisions on whether to implement these programs to help reduce the risk of ACL injuries in their female athletes.

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TABLE OF CONTENTS

ABSTRACT iii

ACKNOWLEDGEMENTS iv

LIST OF TABLES viii

LIST OF FIGURES ix

INTRODUCTION 1

METHODS 3

  Experimental Design 3

  Subjects 3

  Instruments and Procedures 3

  Statistical Analysis 5

RESULTS 6

DISCUSSION 7

PRACTICAL IMPLICATIONS 12

REFERENCES 13

APPENDIX A. PROSPECTUS 19

  Introduction 19

Problem Statement 21

Research Questions 21

Significance of Study 22

Limitations 22

Definition of Terms 22

Literature Review 23

Anterior Cruciate Ligament Definition and Anatomy 23

Prevalence and Mechanism of ACL Injury 24

Predisposing Factors 25

Anatomical characteristics 25

Hormonal characteristics 25

Biomechanical and neuromuscular characteristics 26

Tools to identify risk factors 30

Barriers for predicting risk factors 31

Prevention of ACL Injury 33

Biomechanical training 33

Brain-behavior relationship and motor learning 35

Neuromuscular training programs 36

Age-specific prevention programs 37

Summary 39

Methods 40

Problem Statement 40

Research Questions 40

Experimental Design 40

Subjects 41

Procedures 41

Statistical Analysis 43

References 43

APPENDIX B. INSTITUTIONAL REVIEW BOARD APPROVAL 47

APPENDIX C. DEMOGRAPHIC FORM 48

APPENDIX D. DROP-JUMP 49

APPENDIX E. LANDING ERROR SCORING SYSTEM (LESS) 50

APPENDIX F. NEUROMUSCULAR TRAINING PROTOCOL 51

LIST OF TABLES

Table Page

1. Subject Demographic Information 16
2. LESS Scoring Criteria 16
3. Mean Values for LESS Scores, Maximum Knee Flexion, and Maximum Knee Valgus 17

LIST OF FIGURES

Figure Page

1. LESS Scores vs. Time.. 17

2. Knee Flexion vs. Time.. 18

3. Knee Valgus vs. Time.. 18

INTRODUCTION

An anterior cruciate ligament (ACL) injury is common in female competitive and recreational athletes. Female athletes have a 4- to 6-fold higher risk than male athletes.[1] The result of an ACL injury is costly physically, psychologically, and financially. The total expenditure for surgical repair, rehabilitation, and future services for female athletes who have suffered ACL injury is estimated to be over $17,000 for each individual case.[2]

According to the National Collegiate Athletic Association (NCAA) Injury Surveillance System, women athletes playing collegiate soccer had a knee injury rate about 2.4 times higher than male soccer players and an ACL injury rate at least twice as high as male soccer players over a 5-year period.[3] Collegiate female basketball players had an average knee injury rate about 4.1 times higher than male basketball players over the study period and an ACL injury rate at least three times as high as male basketball players 4 of the 5 years sampled.[3] Differences in injury rates have been linked to underlying extrinsic and intrinsic factors such as level of conditioning, playing style, ligament dominance, leg dominance, quadriceps dominance, and trunk dominance.[4,5] Some predisposing factors that increase the risk of injury may be due to gender differences. Females are more likely to land with less hip and knee flexion which reduces energy absorption in the lower extremity therefore placing more stress on the ligaments.[6,7] Also, females predominantly have increased valgus knee motion and recruit their lateral quadriceps more than their medial quadriceps resulting in an increased anterior shear force on the knee.[8,9]

Due to the female population having an increased risk and much higher rate of ACL injury, clinicians need to identify and address the specific risks to decrease the injury rate in the female population. Many predisposing factors have been discovered relating to injury of the ACL and can be identified by using evaluation tools such as the Landing Error Scoring System

(LESS). Although tools like the LESS can identify common predisposing factors, a specific prevention method has not been indicated for ACL injury. Many researchers try to create prevention programs that will address a majority of the predisposing factors but a single program has not been named as the gold-standard for ACL injury prevention .[1,4,10,11,12,13] Several prevention programs for ACL injury exist and focus on the biomechanical and neuromuscular risk factors of the injury. These programs implement exercises pertaining to core strengthening, trunk and hip control, plyometric training, and lower extremity muscle strengthening.[1,4,10,11,13] Neuromuscular prevention programs have shown to improve overall athletic performance and reduce many risk factors associated with ACL injury.[1,10,11,12,13] The neuromuscular training programs include plyometrics and trunk and hip control exercises which help strengthen the core, improve proprioception, and enhance landing mechanics.[10]

The purpose of this study was to evaluate the biomechanical factors associated with ACL injury in Division II female collegiate athletes (soccer and volleyball) before, during (2 wks, 4 wks, 6 wks), and after an 8-week neuromuscular training program using the LESS. The study focused on identifying significant biomechanical improvements at different time points over the 8-week period. This study will contribute to athletic trainers' knowledge of neuromuscular training programs and their effectiveness to decrease biomechanical risk factors associated with ACL injury in female athletes. By improving the biomechanical characteristics associated with ACL injury in female athletes, the female athlete is less likely to suffer from ACL injury which will benefit her physically, psychologically, and financially. In addition, the athlete may notice improvement in her overall athletic performance after participating in a neuromuscular training program.

METHODS

Experimental Design

A one-group design with repeated measures at five time points was used to guide data collection. The intervention was an 8-week neuromuscular training program and the independent variable was time (pre-training, 2 wks, 4 wks, 6 wks, and post-training). The dependent variables were the Landing Error Scoring System (LESS) score, knee valgus angle, and knee flexion angle.

Subjects

Twenty-four female athletes participating in volleyball or soccer volunteered for the study. Nineteen athletes (10 soccer, 9 volleyball) completed the study. Body anthropometrics for the nineteen athletes who completed the study are represented in Table 1. Subjects were excluded from the study if they had experienced an ACL surgery in the past year, unless cleared by a physician, or self-reported any neurologic, cardiovascular, or neuromuscular diseases. Six out of the twenty-four (25%) participants had suffered an ACL injury prior to the study and three out of the twenty-four (12.5%) had other knee injuries. A majority of the participants were underclassmen (87.5%, Freshmen = 13, Redshirt Freshmen = 1, Sophomores = 7,) and only three were upperclassmen (12.5%, Juniors = 3, Seniors = 0). All subjects participated in a strength and conditioning program concomitantly with the neuromuscular training program.

Instruments and Procedures

Subjects filled out a demographic form and signed an informed consent form. Body anthropometrics (height, weight, and body mass index) were measured and calculated for each subject. Also, during this time the importance of adherence to the program was discussed.

The subjects were asked to wear spandex shorts and a sports bra or a spandex tank top. Anatomical markers were placed on their bodies at the acromioclavicular joint, manubrium, greater trochanter, anterior superior iliac spine (ASIS) (R/L), lateral joint line of the knee, middle of the patella (R/L), tibial tuberosity (R/L), lateral malleolus, and ankle mortise (R/L). The subjects performed a drop-jump off a 30-cm high box to a distance of 50% of their height away from the box, onto the floor, and then performed a maximal vertical jump upon landing. Subjects attended a familiarization session to familiarize them with the drop-jump. The subjects were evaluated on five separate occasions (pre-training, 2nd, 4th, 6th week of training, and post-training). The LESS scoring system (see Table 2) was used to evaluate the drop-jump. The drop-jump was recorded using two standard video cameras (Sony HDR-XR520V, San Diego, CA). One camera was placed to capture movement in the frontal plane and the other was placed to capture movement in the sagittal plane during the jump-landing procedure. The co-investigator evaluated each subject based on the LESS criteria. The LESS is a score based on the number of errors the subject performs during the jump-landing task. The LESS scoring system has a high reliability ($ICC_{2,1}$=0.91, $ICC_{2,k}$= 0.84).[14] A higher score indicates poor landing technique whereas a lower score indicates a better landing techniqueEach jump recorded by the two video cameras was placed into Dartfish video software (Dartfish USA, Alpharetta, GA) so the co-investigator could assess the 17 different items and measure the amount of knee valgus and knee flexion. Subjects were re-evaluated after 2, 4, and 6 weeks into the neuromuscular training as well as a final post-training evaluation after the eighth week. The subjects' total scores for each time point were recorded for further statistical analysis to assess changes in biomechanical factors during the neuromuscular training program.

Participants performed a neuromuscular training protocol as described by Myer et al.[10] This neuromuscular program targets deficits in the trunk and hip. Subjects performed 13 exercise progressions each with five difficulty levels (phases) which help facilitate progress within the program. The exercise progressions (lateral jumping, single-leg anterior, prone trunk stability, kneeling trunk stability, single-leg lateral, tuck jump, lunge, lunge jump, hamstring-specific, single-leg rotatory, lateral trunk, trunk flexion, and trunk extension) within this neuromuscular training program are designed to improve the subjects' ability to control her trunk and improve core stability during dynamic movement. The difficulty of the task increases with each new phase of the progression. In order to progress to the next phase, the subject had to master the previous phase. Mastering the phase was determined by observation by the co-investigator on how easily the subject performed the maneuver and her technique. The research team provided feedback to the subjects about their technique but the co-investigator was the only one determining when the subject moved to the next phase. The subjects participated in the neuromuscular training program three times per week over an 8-week period. All procedures were approved by the Institutional Review Board and subjects provided written consent.

Statistical Analysis

Mean differences in LESS scores, knee valgus, and knee flexion were analyzed with a one-way repeated measures ANOVA over five time points. A paired samples t-test was used to compare pre- and post- test values of the LESS scores, knee flexion, and knee valgus. An alpha level of 0.05 was used to test for significance. A Bonferroni adjustment for multiple comparisons was used to compare LESS scores, knee flexion angles, and knee valgus angles between each time point and the previous time point. Statistical analyses were conducted with SPSS (IBM SPSS Statistics 20.0, Armonk, NY).

RESULTS

The female athletes' LESS scores changed over the 8-week period but did not improve from pre- to post- test, $F_{4,15} = 4.244$, $P = 0.017$. Although significance is noted with $P < .05$, the significance is due to the LESS score increasing from pre-test (5.26 ± 1.15) to the 2nd week (6.10 ± 1.10), $P = 0.029$. Unfortunately, the increase in LESS scores was in the wrong direction therefore, the significance does not represent an improvement. Table 3 contains the mean values and Figure 1 shows the distribution over the eight weeks. Their maximum knee flexion did not improve during the neuromuscular training program and decreased from 76.8 ± 7.5° to 79.1 ± 8.3°. However, the change in maximum knee flexion was not significant from pre- to post- test and there was no significant difference between each time point; $F_{4,15} = 0.537$, $P = 0.725$. Table 3 contains the mean values for knee flexion angles and Figure 2 shows the distribution over the eight weeks. The female athletes' maximum knee valgus angles did significantly decrease while participating in the neuromuscular training program, $F_{4,14} = 5.296$, $P = 0.001$. The knee valgus angles significantly improved from pre- to post- test; however, knee valgus angles increased from the 2nd week (5.44 ± 6.99°) to the 4th week (9.96 ± 8.64°), $t_{17} = 3.244$, $P < 0.001$. Table 3 contains the mean values for knee valgus angles and Figure 3 shows the distribution over the eight weeks. Maximum knee valgus angles of the female athletes significantly decreased after the 8-week neuromuscular training program. Maximum knee flexion angles increased but not significantly and LESS scores did not improve over the 8-week period.

DISCUSSION

The purpose of this study was to determine the effects of an 8-week neuromuscular training program on LESS scores, maximum knee flexion, and maximum knee valgus. Maximum knee flexion, maximum knee valgus, and LESS scores are common measures which help indicate an individual's susceptibility to an ACL injury. This study used these criteria to determine the effects of neuromuscular training to help prevent non-contact ACL injuries in female athletes.

In this study, maximum knee valgus angles in female collegiate athletes significantly decreased after implementing an 8-week neuromuscular training program. Neuromuscular training may be an exceptional intervention for at-risk female athletes or female athletes in general to decrease maximum knee valgus and help equalize the incidence of non-contact ACL injuries between female and male athletes. Significant improvement was noted within eight weeks of neuromuscular training and by elongating the training period the female athletes may experience even greater improvement in maximum knee valgus. Chappell and Limpisvasti[13] conducted a 6-week neuromuscular training program consisting of 10 exercises (performed 6 days/week) focusing on core strengthening, dynamic joint stability and balance training, jump training, and plyometric exercises. They found no significant difference in maximum knee valgus from baseline to the end of the 6-week neuromuscular training. These two opposite findings from this study and the present study suggest that the length of the program may be a key component for success. A hypothesis for the significant decreases in maximum knee valgus during this specific 8-week neuromuscular training program is that the female athletes 1) recruited the medial quadriceps and more of the hip/trunk musculature and 2) became stronger in their hip/trunk and knee musculature. These changes in strength and neuromuscular control would increase the stability of the joint resulting in less ligament dominance, creating a reduced amount of knee valgus. However, the duration of neuromuscular training may be a crucial factor in the success of improving maximum knee valgus and/or other biomechanical factors.

Along with knee valgus, knee flexion may be a main contributor to non-contact ACL injuries in female athletes. After eight weeks of neuromuscular training, the female athletes' maximum knee flexion decreased. This indicates that there was no improvement during the study after the eight weeks of neuromuscular training. However, previous studies[13,15] found conflicting results, showing improvement in maximum knee flexion, knee flexion at initial contact, and knee flexion displacement. Chappell and Limpisvasti[13] observed improvement in maximum knee flexion during the landing phase of a drop-jump task after only six weeks of neuromuscular training. Concurrently, DiStefano et al[15] conducted an individual item analysis on the variables of the LESS and found improvement in knee flexion at initial contact and knee flexion displacement over both a 4-month and 9-month training period. If females increase knee flexion during the landing phase and delay energy absorption they can reduce the vertical ground reaction moment and the internal hip extension moment which will serve as a protective mechanism for the ACL.[6,7] Landing with increased flexion in the knee will reduce the risk factor of ligament dominance because the ligament's integrity is less likely to be compromised and energy absorption will occur through the lower extremity musculature. According to other studies,[7,15] measuring knee flexion displacement (the amount of change from initial contact to maximum knee flexion) over the landing phase instead of maximum knee flexion may give a better indication of the amount of energy absorption over the landing phase.

Another measurement of interest in the present study was the LESS score. The LESS is an inexpensive tool that helps identify biomechanical errors and jump-landing strategies of individuals during a drop-jump. LESS scores are categorized into four subsections: excellent (less than or equal to 4), good (>4 to less than or equal to 5), moderate (>5 to less than or equal to 6), and poor (>6) on a scale from 0-19. A higher score indicates poor landing mechanics which may result in an increased risk for injury. The LESS scores of the female athletes significantly changed over the 8-week period; however, the only significant change was noted between the pre-test and second week where the score increased indicating the scores got worse over those two weeks. The female athletes' mean LESS scores throughout the eight week training period ranged from 5.26 to 6.11, categorizing their landing mechanics between moderate and poor. It is unclear why the LESS scores increased within the first two weeks of the neuromuscular training and there is limited research to compare results. However, DiStefano et al[15] conducted a study using two injury prevention programs and all subjects improved their landing movements (LESS scores). Also, they found that those individuals who had "poor" landing techniques improved their LESS scores greater than the "good", "moderate", and "excellent" groups. The researchers concluded that neuromuscular training programs are most effective with athletes who display poor landing techniques prior to the start of the program. They suggest clinical screening tools should be used to identify individuals with high-risk biomechanics and these high-risk individuals should participate in injury prevention programs to enhance the effectiveness.

The main finding of this study is that the female athletes had reduced knee valgus during a drop-jump after an 8-week neuromuscular training program; however, knee flexion and LESS scores did not significantly change from pre- to post- training. The uniqueness of this study comes from the combination of using this specific neuromuscular training protocol and evaluating its effectiveness by using the LESS criteria, measuring maximum knee valgus, and measuring maximum knee flexion. Although this study found significant improvement in only one factor, the existing literature continues to support that participating in neuromuscular training can improve various biomechanical factors. Myer et al[11] observed decreases in knee internal valgus torque and knee internal varus torque, as well as an increase in flexion-extension ROM. Not only did they see improvements in biomechanical characteristics but also they observed improvement in performance measures. Chappell and Limpisvasti[13] produced similar results when assessing the effects of a different 6-week neuromuscular training program focusing on plyometric training and core strengthening. They noticed a decrease in dynamic knee valgus moment during the landing phase of a stop jump task and an increase in initial knee flexion and maximum knee flexion angles during the landing phase of drop jump tasks. The subjects' performance values increased for vertical jump and both single-legged hop tests. There is sufficient evidence to support the fact that neuromuscular training programs improve biomechanical characteristics and performance but there is limited research in their role of preventing ACL injuries in female athletes.

The main limitation of this study was the lack of a control group. No comparisons between groups (control vs. neuromuscular training) could be made, only comparisons from each time point. Another limitation is that the results cannot be generalized to other athletes (high school, Division I, etc.).

Future research in the effects of neuromuscular training should follow a randomized controlled trial research design, use blind evaluators, and recruit a larger subject group to obtain better results. In addition, lengthening the neuromuscular training program from eight to 12 weeks (or longer) in order to see more/significant improvement in LESS scores, maximum knee valgus, and maximum knee flexion should be considered. Also, researchers may want to measure knee flexion displacement rather than maximum knee flexion which may be a better indicator of the amount of energy absorption occurring during the landing phase. Overall, more research needs to be conducted in this area of study to provide conclusive evidence about the effects of neuromuscular training on LESS scores, knee valgus, and knee flexion. The most important aspect for future research is the need to perform longitudinal studies to report the effectiveness of neuromuscular training programs on the prevention of ACL injuries in female athletes. Researchers should use a long-term neuromuscular training program, collect biomechanical data, and perform injury surveillance over several years to observe the relationship between biomechanical characteristics and ACL injury rate. If future research can provide more conclusive evidence, neuromuscular training may become the gold-standard for prevention of non-contact ACL injuries in female athletes.

PRACTICAL IMPLICATIONS

Athletic trainers should utilize neuromuscular training in their clinical practice to help reduce some of the biomechanical risk factors associated with ACL injuries in their female athletes. The training takes only 15 to 30 minutes per day and may be performed 3 to 5 times per week. It can be easily incorporated into pre-activity routines and may aid as a warm-up for the athletes. The LESS is a reliable tool that clinicians can use to track the change in biomechanical characteristics over the neuromuscular training period for their athletes. Also, clinicians can use the LESS at mass screenings of athletes because it is relatively inexpensive and is less time consuming than the laboratory-based method (3-D motion analysis). The LESS can help clinicians identify risky behaviors performed by the athlete and their biomechanical predispositions to injury. LESS scores will assist clinicians in creating a specific neuromuscular prevention program for each individual to correct his or her biomechanical dysfunctions and decrease his or her risk of injury to the ACL.

REFERENCES

1. Lim BO, Lee YS, Kim JG, An KO, Yoo J, Kwon YH. Effects of sports injury prevention training on the biomechanical risk factors of anterior cruciate ligament injury in high school female basketball players. *Am J Sports Med.* 2009; 37:1728-1734.

2. Grindstaff TL, Hammill RR, Tuzson AE, Hertel J. Neuromuscular control training programs and noncontact anterior cruciate ligament injury rates in female athletes: numbers-needed-to-treat analysis. *J Athl Train*. 2006; 41:450-456.

3. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer. *Am J Sports Med.* 1995; 23:694-701.

4. Hewett TE, Ford KR, Hoogenboom BJ, Myer GD. Understanding and preventing ACL injuries: current biomechanical and epidemiologic considerations - update 2010. *N Am J Sports Phys Ther*. 2010; 5:234-251.

5. Prentice WE. The knee and related structures. *Arnheim's Principles of Athletic Training—A Competency-Based Approach.* 12th ed. New York, NY: McGraw-Hill; 2006:629-632.

6. Beutler AI, de la Motte SJ, Marshall SW, Padua DA, Boden BP. Muscle strength and qualitative jump-landing differences in male and female military cadets: The jump-ACL study. *J Sports Sci and Med*. 2009; 8:663-669.

7. Norcross MF, Blackburn JT, Goerger BM, Padua DA. The association between lower extremity energy absorption and biomechanical factors related to anterior cruciate ligament injury. *Clin Biomech*. 2010; 25:1031.

8. Myer G, Ford KR, Hewett TE. The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *J Electromyogr Kinesiol*. 2005; 15:181-189.

9. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc*. 2003; 35:1745-1750.

10. Myer GD, Chu DA, Brent JL, Hewett TE. Trunk and hip control neuromuscular training for the prevention of knee joint injury. *Clin Sports Med*. 2008; 27:425-448.

11. Myer D, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J. Strength Cond. Res*. 2005; 19:51–60.

12. Myer GD, Ford KR, Hewett TE. Methodological approaches and rationale for training to prevent anterior cruciate ligament injuries in female athletes. *Scand J Med Sci Sports*. 2004; 14:275-285.

13. Chappell JD and Limpisvasti O. Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *Am J Sports Med.* 2008; 36:1081-1086.

14. Padua DA, Marshall SW, Boling MC, Thigpen CA, Garrett Jr WE, Beutler AI. The Landing Error Scoring System (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics: The JUMP-ACL study. *Am J Sports Med.* 2009; 37:1996-2002.

15. DiStefano LJ, Padua DA, DiStefano MJ, Marshall SW. Influence of age, sex, technique, and exercise program on movement patterns after an anterior cruciate

ligament injury prevention program in youth soccer players. *Am J Sports Med*. 2009; 37:495-505.

Table 1. Subject Demographic Information

	Mean	SD
Age	19.05	±0.62
Height (cm)	173.16	±9.41
Weight (kg)	68.26	±8.86
BMI (kg/m^2)	22.76	±2.40

Table 2. LESS Scoring Criteria

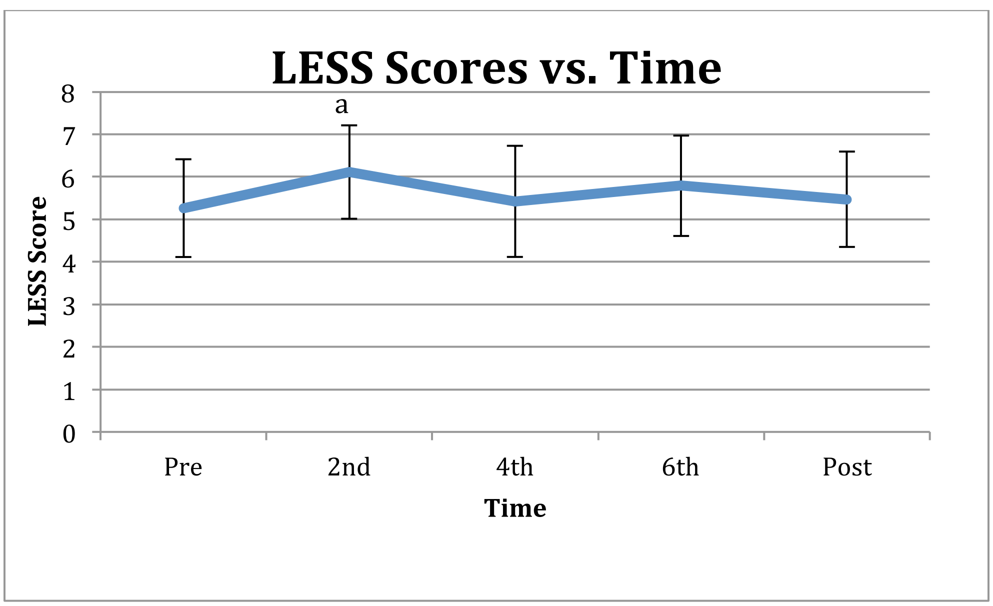
1. **Knee Flexion @ Initial Contact: > 30 degrees**
   ____ Yes (0)
   ____ No (+1)
2. **Knee Valgus @ Initial Contact: Knees over midfoot**
   ____ Yes (0)
   ____ No (+1)
3. **Hip Flexion @ Initial Contact: Hips are flexed**
   ____ Yes (0)
   ____ No (+1)
4. **Trunk Flexion @ Initial Contact: Trunk is flexed**
   ____ Yes (0)
   ____ No (+1)
5. **Lateral Trunk Flexion @ Initial Contact: Trunk is vertical**
   ____ Sternum centered over hips (0)
   ____ Lateral deviation of sternum over hips (+1)
6. **Ankle Plantar Flexion @ Initial Contact: Toe to heel**
   ____ Yes (0)
   ____ No (+1)
7. **Foot Position @ Initial Contact: Toes > 30 of ER**
   ____ Yes (+1)
   ____ No (0)
8. **Foot Position @ Initial Contact: Toes > 30 of IR**
   ____ Yes (+1)
   ____ No (0)
9. **Stance Width @ Initial Contact:< Shoulder width**
   ____ Yes (+1)
   ____ No (0)
10. **Stance Width @ Initial Contact:> Shoulder width**
    ____ Yes (+1)
    ____ No (0)
11. **Initial Foot Contact: Symmetric**
    ____ Yes (+0)
    ____ No (+1)
12. **Knee Flexion Displacement: > 45 degrees**
    ____ Yes (0)
    ____ No (+1)
13. **Knee Valgus Displacement: ≥ great toe**
    ____ Yes (+1)
    ____ No (0)
14. **Hip Flexion Displacement: Hips flex more than at initial contact**
    ____ Yes (0)
    ____ No (1)
15. **Trunk Flexion Displacement: Trunk flexes more than at initial contact**
    ____ Yes (0)
    ____ No (1)
16. **Joint Displacement (Sagittal Plane)**
    ____ Soft (0)
    ____ Average (+1)
    ____ Stiff (+2)
17. **Overall Impression**
    ____ Excellent (0)
    ____ Average (+1)
    ____ Poor (+2)

Adopted from Padua D (2011). *Identifying Modifiable Risk Factors for ACL Injury and Re-injury.*

Table 3. Mean Values for LESS Scores, Maximum Knee Flexion, and Maximum Knee Valgus

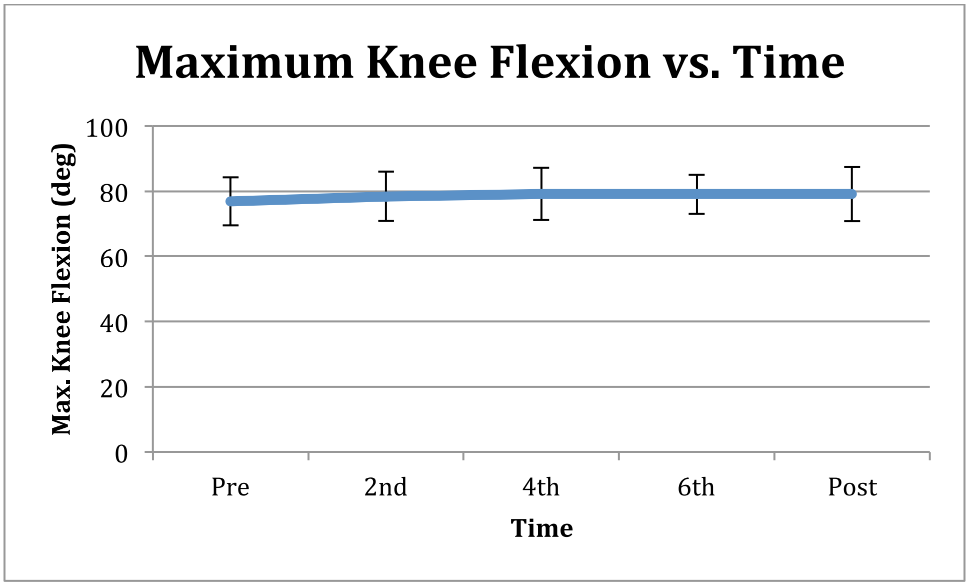
	Pre	**2^{nd}**	**4^{th}**	**6^{th}**	**Post**
LESS Scores	5.26 ± 1.15	6.11 ± 1.10	5.42 ± 1.31	5.79 ± 1.18	5.47 ± 1.12
Max. Knee Flexion (°)	76.89 ± 7.41	78.42 ± 7.52	79.21 ± 8.02	9.11 ± 6.02	79.11 ± 8.31
Max. Knee Valgus (°)	11.18 ± 10.70	5.44 ± 6.99	9.96 ± 8.64	6.59 ± 7.59	5.79 ± 6.09

Figure 1. LESS Scores vs. Time



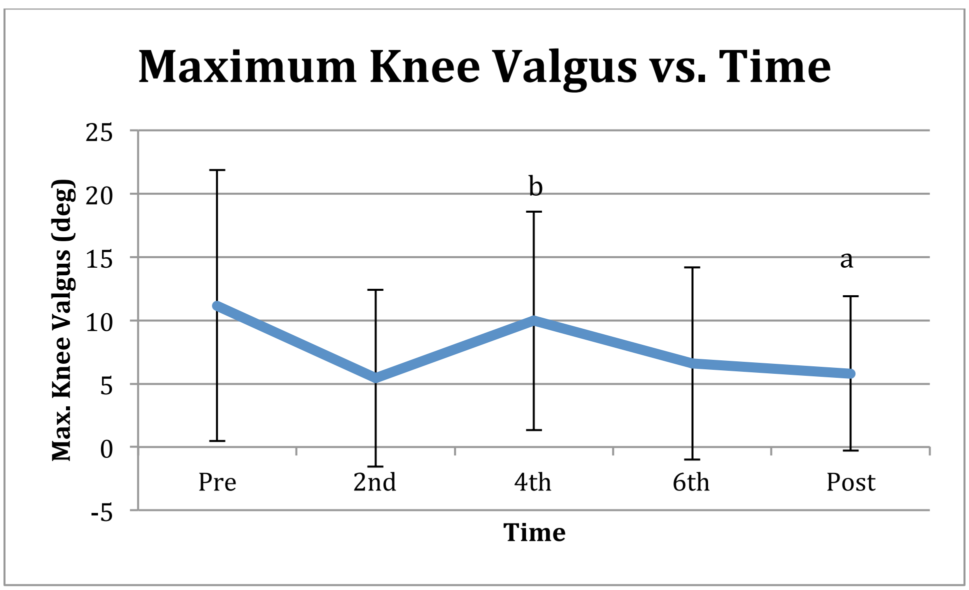
LESS scores at Pre, 2^{nd}, 4^{th}, 6^{th}, and Post (means ± SD)
a = significantly different from Pre, $p < 0.05$

Figure 2. Maximum Knee Flexion vs. Time



Maximum knee flexion at Pre, 2nd, 4th, 6th, and Post (means ± SD)

Figure 3. Maximum Knee Valgus vs. Time



Maximum knee valgus at Pre, 2nd, 4ht, 6th, and Post (means ± SD)
a = significantly different from Pre; b = significantly different from 2nd, $p < 0.05$

APPENDIX A. PROSPECTUS

Introduction

An anterior cruciate ligament (ACL) injury is common in female competitive and recreational athletes. Female athletes have a 4- to 6-fold higher risk than male athletes.[1] According to the National Collegiate Athletic Association (NCAA) Injury Surveillance System, women athletes playing collegiate soccer had a knee injury rate about 2.4 times higher than male soccer players and an ACL injury rate at least twice as high as male soccer players over a 5-year period.[2] Collegiate women's basketball players had an average knee injury rate about 4.1 times higher than male basketball players over the study period and an ACL rate at least three times as high as men's basketball players 4 of the 5 years sampled.[2] The total expenditure for surgical repair, rehabilitation, and future services for females athletes who have suffered ACL injury are estimated to be over $17,000 for each individual case.[3] The role of the ACL is to prevent the femur from moving posteriorly on the tibia, to stabilize the tibia against excessive internal rotation, and to restrain valgus and varus stresses at the knee.[4] Injuries to the ACL may occur because of direct contact with another athlete or object, or from a noncontact mechanism (sharp, cutting motion), most commonly an incorrect landing technique. Differences in injury rates have been linked to underlying extrinsic and intrinsic factors such as level of conditioning, playing style, ligament dominance, leg dominance, quadriceps dominance, and trunk dominance.[4,5] Several factors play a role in injury to the ACL such as gender, hormones, neuromuscular characteristics, and biomechanical characteristics.[4-11]

Some predisposing factors that increase the risk of injury may be due to gender differences. Females are more likely to land with less hip and knee flexion which reduces energy absorption in the lower extremity therefore placing more stress on the ligaments.[6,7] Also, females predominantly have increased valgus knee motion and recruit their lateral quadriceps more than their medial quadriceps resulting in an increased anterior shear force on the knee.[8,9] The fluctuation of hormones during the menstrual cycle is another factor that is thought to play a role in differences between ACL injury rates. Many believe that the fluctuations of hormones change the neuromuscular and biomechanical characteristics within the knee[10,11] but researchers have not observed any significant differences in knee joint laxity, neuromuscular characteristics, and biomechanical characteristics throughout the menstrual cycle.[11] However, some have observed a decrease in musculotendinous stiffness during the ovulatory phase which may be a possible risk factor for ACL injury.[10]

Due to the female population having an increased risk and much higher rate of ACL injury, clinicians need to identify and address the specific risks to decrease the injury rate in the female population. Many predisposing factors have been discovered relating to injury of the ACL and can be identified by using evaluation tools such as the Landing Error Scoring System (LESS). Along with the LESS tool, researchers utilize laboratory-based measurements and clinical-based measurements to identify and predict the risk of ACL injury. The laboratory-based technique uses three-dimensional hip, knee, and ankle kinematic and kinetic data whereas the clinic-based technique uses a standard camcorder and MATLAB (a numerical computing environment and programming language software) to identify predisposing biomechanical factors.[12] These tools can help identify the risk factors associated with ACL injury and ultimately reduce injury rate by implementing a specific prevention program to target those factors.

Although common predisposing factors can be identified by tools like the LESS, a specific prevention method has not been indicated for ACL injury. Many researchers try to create prevention programs that will address a majority of the predisposing factors but a single program has not been named as the gold-standard for ACL injury prevention.[1,5,13-16] Several prevention programs for ACL injury exist and focus on the biomechanical and neuromuscular risk factors of the injury. These programs implement exercises pertaining to core strengthening, trunk and hip control, plyometric training, and lower extremity muscle strengthening.[1,5,13,14,16] Neuromuscular prevention programs have shown to improve overall athletic performance and reduce many risk factors associated with ACL injury.[1,13-16] The neuromuscular training programs include plyometrics and trunk and hip control exercises which help strengthen the core, improve proprioception, and enhance landing mechanics.[13] If these types of programs are implemented in women athletics they can greatly reduce the risk of injury to the ACL and increase their overall athletic performance.[14,16]

Problem Statement

The purpose of this study was to evaluate the biomechanical factors associated with ACL injury in Division II female collegiate athletes (soccer and volleyball) before, during (2 wks, 4 wks, 6 wks), and after an 8-week neuromuscular training program.

Research Questions

1. Did the LESS scores decrease after participating in an 8-week neuromuscular training program?
2. Was there significant improvement at 2 wks, 4 wks, 6 wks, and 8 wks?

3. Did knee valgus angles decrease after an 8-week neuromuscular training program?
4. Did knee flexion angles increase after an 8-week neuromuscular training program?

Significance of Study

The significance of this study was to advance the knowledge in the area of neuromuscular training programs to decrease biomechanical risk factors associated with ACL injury in female athletes. The uniqueness of this study was that it focused on identifying significant biomechanical improvements at different time points over an 8-week period. By improving the biomechanical characteristics associated with ACL injury in female athletes, the female athlete is less likely to suffer from ACL injury which will benefit her physically, psychologically, and financially. Also, neuromuscular training programs have been proven to increase overall athletic performance.

Limitations

1. The results of the study can be applied only to DII collegiate female athletes.
2. A control group is not included to make a comparison.
3. The neuromuscular program takes place for only eight weeks.
4. The LESS is the only evaluation tool being used.

Definition of Terms

<u>Anterior cruciate ligament (ACL):</u> ligament that prevents the femur from moving posteriorly during weight bearing and stabilizes the tibia against excessive internal rotation.[4]

Knee valgus: a force acting on the lateral (outside) of the knee, bending the lower leg outward from the midline; knock-kneed.[4]

Knee varus: a force acting on the medial (inside) of the knee, bending the lower leg toward the midline; bow-legged.[4]

Landing Error Scoring System (LESS): an inexpensive clinical assessment tool developed to provide a standardized instrument for identifying potentially high-risk movement patterns during a jump-landing maneuver.[20]

Neuromuscular: pertaining to the nerves and the muscles.[25]

Literature Review

The purpose of this literature review was to discuss the role of the anterior cruciate ligament (ACL), the prevalence and mechanism of injury, the predisposing factors to injury, and methods to prevent injury. The majority of the review focused on the specific characteristics that predispose individuals to ACL injury and training programs that may correct those characteristics to reduce the risk of injury.

Anterior Cruciate Ligament Definition and Anatomy

The ACL is a crucial ligament for the stability of the knee joint. The ACL is an intracapsular ligament which means it is within the articular capsule of the knee joint along with the posterior cruciate ligament (PCL). The ACL travels from the anterior portion of the tibial plateau to the posteromedial aspect of the lateral condyle of the femur. The PCL does the exact opposite and runs from the posterior aspect of the tibial plateau to the anteromedial side of the lateral condyle of the femur. The ACL stabilizes the knee joint from anterior translation of the tibia on a fixed femur, posterior translation of the femur on a fixed tibia, and hyperextension of the knee.[17] The PCL resists posterior displacement of the tibia on a fixed femur and is known to be the primary stabilizer of the knee.[17] The ACL is weaker and smaller than the PCL and is more prone to injury.[17] Injury to the ACL is one of the most devastating injuries to the knee joint because of the physical disability, expenses, and future complications associated with this injury.

Prevalence and Mechanisms of ACL Injury

Anterior cruciate ligament injury occurs from a direct blow to the knee, from rotation of the lower leg while the foot is still planted, and from a hyperextension force while the foot is fixed.[5] Non-contact injury to the ACL is more prevalent in sports consisting of running, cutting, and jumping. Some authors[18] report that 70% to 80% of ACL injuries occur during non-contact sporting events and this number continues to rise due to increased involvement in these activities.

Female athletes have a 4- to 6-fold higher risk of ACL injuries when compared to their male counterparts.[1] Multiple factors play a role in this gender difference and a combination of these factors place females at a greater risk. Hewett et al[5] discussed the extrinsic and intrinsic factors underlying the gender differences in the incidence of ACL injury. Some theories propose that physical and visual perturbations, bracing, and shoe-surface interactions relate to ACL injury. The authors[5] focus on identifying the intrinsic factors, neuromuscular and biomechanical risk factors, associated with injury. Four neuromuscular components that may assume a role in the higher incidence of ACL injury in females are 1) leg dominance, 2) ligament dominance, 3) quadriceps dominance, and 4) trunk dominance.[5] Current researchers are investigating the many risk factors associated with ACL injuries in females to identify the problem and make specific alterations to reduce their risk.

Predisposing Factors

ACL injuries are thought to be from differences in anatomical characteristics[19], hormonal characteristics[10,11], and biomechanical or neuromuscular characteristics.[5,6-9] Researchers have investigated these multiple characteristics to help pinpoint the risk factors that contribute to the disparity between genders.[5-11,19]

Anatomical characteristics. Evidence of anatomical differences increasing the risk of injury is lacking and controversial. Differences in anatomical characteristics have been identified between males and females. In a consensus statement, Shultz et al[19] discuss the possible structural risk factors attributed to ACL injury. The female ACL is shorter in length, cross-sectional area, and volume when compared to male counterparts. Females' femoral notch height is higher and the femoral notch angle is smaller which may lead to femoral notch impingement. The ACL in females tend to be less stiff and fail at lower load levels. However, it is unknown how/if these anatomical factors influence knee joint neuromechanics that may increase the risk of injury. The roles of anatomical and hormonal characteristics have been overshadowed by the emphasis on the biomechanical and neuromuscular characteristics that contribute to the higher incidence of ACL injury in females.

Hormonal characteristics. Hormonal characteristics especially during the different phases of the menstrual cycle may assume a role in the differences between genders but the literature is conflicting. No significant differences have been found between the phases of the menstrual cycle when evaluating fine motor coordination, postural stability, hamstrings-quadriceps strength ratio, knee flexion excursion, knee valgus excursion, peak proximal tibial anterior shear force, flexion moment at peak proximal tibial anterior shear force, and valgus moment at peak proximal tibial anterior shear force.[11] Accordingly, fluctuations of hormones, estrogen and progesterone, during the menstrual cycle have no effect on anterior knee joint laxity but researchers have detected a decrease in musculotendinous stiffness during the ovulatory phase of the cycle.[10] The decrease in musculotendinous stiffness may be a risk factor for injury because a more compliant muscle may not be able to counteract the forces placed on the knee and the ligaments may be compromised.[10] Overall the fluctuations in hormones during the menstrual cycle has not been ruled out as a predisposing factor to injury but more research needs to be conducted in order to prove that either does or does not play a role in ACL injury in females.

Biomechanical and neuromuscular characteristics. A majority of the research[5,6-9] addresses biomechanical or neuromuscular differences which may be implications for the higher incidence of injury in females. As stated previously, leg dominance, ligament dominance, quadriceps dominance, and trunk dominance are four common components attributed to the differences in genders. Leg dominance is simply having one leg that is dominant or stronger than the other which leads to a side-to-side asymmetry. This may be a possible predisposition to injury because more force is placed on the dominant leg. Ligament dominance is when static stabilizers and the bony anatomy absorb the forces during activity instead of the muscles surrounding the joint.[5] Ligaments and bones are not as compliant as muscles and do not accommodate forces placed on them during activity as well as muscles. If a female is ligament dominant she will need to work on activating and strengthening the musculature surrounding the knee. This will allow the forces to be absorbed more easily and decrease the stress placed on the bones and ligaments, which will reduce her risk of injury. Quadriceps dominance is the tendency to stabilize the knee joint by primarily using the quadriceps muscles instead of other knee musculature such as the hamstring group.[5] Trunk dominance is the ability to control the trunk precisely in a three-dimensional space.[5] Females have a greater risk of injury because they are unable to adequately sense the position of their trunk and allow greater movement after disturbance to the trunk.[5]

Jump-landing strategies. Buetler et al[6] conducted a prospective cohort study comparing the jump-landing strategies of males and females. They used the Landing Error Scoring System (LESS) to identify biomechanical differences between genders. The overall LESS scores were significantly different; the mean score for males was 4.65 ± 1.69 whereas females' mean score was 5.34 ± 1.51. The LESS scores are categorized into four subsections: excellent (less than or equal to 4), good (>4 to less than or equal to 5), moderate (>5 to less than or equal to 6), and poor (>6) on a scale from 0-19. A higher score indicates poor landing mechanics which may result in an increased risk for injury. The scores are based on biomechanical errors made during a jump-landing task. Females are more likely to land with less hip and knee flexion at the initial contact of the landing phase as well as landing in a wider stance with greater knee valgus and less knee flexion displacement over the entire landing phase. Males demonstrated landing asymmetrically with their toes out and on their heels.[6] Females exhibit quadriceps dominance when they land with less knee flexion which in turn creates ligament dominance. Overall females have a poorer landing technique when landing from a jump that may increase their risk of injury to the ACL. These differences in biomechanical landing techniques may affect how the body absorbs the forces acting on it. Because females have less knee flexion over the landing phase the lower extremity is less efficient in absorbing the energy from the force of landing. Norcross et al[7] investigated the relationships between lower extremity energy absorption and biomechanical risk factors related to ACL injury. They found significant relationships between total energy absorption and peak vertical ground reaction force, anterior tibial shear force, and internal hip extension moment during the initial impact phase of landing. There was a significant relationship between the peak vertical ground reaction force and the internal hip extension moment during the terminal phase of landing. These results indicate that greater total energy absorption during the initial contact phase of landing is associated with greater peak vertical ground reaction force, anterior tibial shear force, and internal hip extension moment, while greater total energy absorption during the terminal phase is associated with lesser peak vertical ground reaction force and internal hip extension moment. If females increase flexion during the landing phase and delay energy absorption they can reduce the vertical ground reaction moment and the internal hip extension moment which will serve as a protective mechanism for the ACL.[6,7] Landing with increased flexion in the knee will reduce the risk factor of ligament dominance because the ligament's integrity is less likely to be compromised and energy absorption will occur through the lower extremity musculature. Another biomechanical risk factor during the landing phase of a jump is increased knee valgus motion.

<u>Valgus knee motion.</u> Greater knee valgus motion is a predisposing factor because it places the individual in a position that increases stress on the ACL. A study[9] conducted to determine gender differences during a landing manuever of high school male and female basketball players demonstrated females have greater knee motion (female 7.3 ±

0.5 cm, male 5.3 ± 0.5 cm) and a higher maximum valgus knee angle (female 27.6 ± 2.2°, male 16.1 ± 2.1°) when compared to males. Also, females had a different maximum valgus angle when compared bilaterally (dominant side 27.6 ± 2.2°, nondominant side 12.5 ± 2.8°); the dominant extremity had a higher maximum valgus angle than the nondominant. This study gives a great example of both ligament dominance and leg dominance. The greater knee motion and higher valgus angles when compared to males is an example of ligament dominance. A female who displays greater knee valgus increases her chance of compromising the integrity of the ACL due to the force placed on the ligament. The imbalance of the side-to-side measurements identifies leg dominance which predisposes a female to ACL injury.[9] Along with side-to-side imbalances, muscle imbalances may be apparent within the musculature of each individual lower extremity.

Muscle imbalance. Muscle imbalances associated with increased risk of ACL rupture are predominantly related to the quadriceps and hamstring groups. Females prefer to recruit more of their quadriceps muscles during the landing phase rather than the hamstrings, which cause muscle imbalances in the lower extremity.[6] Quadriceps' dominance over the hamstrings is a common predisposing factor because it reduces knee flexion during activities and in return increases risk. However, a study conducted by Myer et al[8] demonstrated that females have a discrepancy within the quadriceps group. Females tend to have a decreased ratio of medial quadriceps to lateral quadriceps recruitment when compared with male subjects. Females recruit their lateral quadriceps more than their medial quadriceps which increases the anterior shear force of the knee, which is a common mechanism of injury to the ACL.[8] Other musculature has been related to ACL injury such as the hip musculature and trunk musculature. During a jump-landing study to determine differences in males and females, scientists observed that females with weaker hamstrings and gluteus medius strengths were more likely to use poor landing strategies, which may heighten their risk of injury to the knee joint.[6]

Tools to identify risk factors in females. Tools to identify these poor landing strategies and muscular imbalances are becoming more prevalent in research. If the identification tools are inexpensive and easy to operate clinicians are more likely to use them to identify risks in their female athletes. This will allow them to implement a prevention program specific to the individual's needs. Myer et al[12] investigated the correlation between a laboratory-based prediction tool and a clinic-based prediction tool. The clinic-based nomogram was used to predict high knee abduction moments (KAM) based off measurements of knee valgus motion, knee flexion range of motion, body mass, tibia length, and quadriceps-to-hamstrings ratio The importance of predicting high KAM in females is because this measure is a predisposing factor for injury. The prediction for KAM was first measured using logistic regression analysis from three-dimensional motion analysis (laboratory-based) then compared to the value for the clinic-based technique to observe the correlation between the two.[12] The clinic-based measurements had a high correlation to the laboratory-based measurements ($r = 0.87$ for knee valgus motion, $r = 0.95$ for knee flexion range of motion, $r = 0.98$ for tibial length), resulting in two effective ways to predict the risk of female athletes.[12] The significance behind these findings is that the clinic-based approach is more cost-effective and easier to perform on large groups of athletes whereas the laboratory-based approach is expensive and time demanding.

Another clinic-based approach for measuring females with increased risk for ACL injury is the Landing Error Scoring System (LESS). The Landing Error Scoring System (LESS) is an inexpensive approach to identify biomechanical risk factors in female athletes by assessing their movement in the sagittal, frontal, and transverse planes.[20] Like the other clinical-based assessment mentioned, the LESS was evaluated by comparing it to the gold-standard of laboratory-based three-dimensional motion analysis. The LESS is a reliable and valid tool for identifying females with increased biomechanical risk factors.[20] The LESS had good interrater reliability ($ICC_{2,k} = 0.84$, SEM = 0.71) and excellent intrarater reliability ($ICC_{2,1} = 0.91$, SEM = 0.42).[20] This standardized tool can be used by clinicians at mass screenings of athletes because it is relatively inexpensive and less time consuming than the laboratory-based method. These tools identify risky behaviors performed by the athlete and biomechanical predispositions to injury. The LESS and similar clinic-based techniques to identify risks will help in the creation of specific neuromuscular prevention programs to correct the individual's biomechanical dysfunctions and decrease their risk of injury to the ACL. A drawback of using the LESS approach is that it uses subjective measurements whereas a laboratory-based approach uses objective measurements to evaluate joint kinematics and kinetics; however, the laboratory-based approach is a very expensive and time demanding process.

Barriers for predicting risk factors. The ability to identify risk factors inevitably gives clinicians the advantage because then they are able to implement measures to possibly prevent injury; but barriers exist in predicting risk factors associated with ACL injury. Ali and Rhoui[18] identify the shortcomings and challenges of studying noncontact ACL injuries and elucidate our current understanding of ACL injury mechanisms and risk factors. Injury mechanisms and risk factors associated with ACL injury have been studied for many years and our understanding has grown but the literature is lacking consensus and coherence.[18] The lack of coherence is from studies being conducted with similar experimental designs but having results that contradict each other. An example is the role of hormonal characteristics throughout the menstrual cycle and the risk of ACL injury; the literature is not coherent because the results vary across studies so researchers cannot come to a consensus as to whether the menstrual cycle assumes a crucial role. The reason behind the lack of coherence and consensus in ACL injury research is because injury to the ACL is due to multiple factors. Many studies investigate only a single risk factor pertaining to ACL injury by comparing the intrinsic and extrinsic differences between male and female subjects such as Q-angle, intercondylar notch width, and hormones without taking into account the combination of these effects.[18] Another inherent challenge of ACL research is that in-vivo measurements of ACL loading are rarely performed. The main reason for this is because of the ethical considerations in performing in-vivo studies on human subjects.[18] This accounts for a disadvantage to the researchers because they cannot clearly investigate the structural loading of the ACL during functional movement. Scientists most often use an in-vitro experimental method which assists in predicting injury mechanisms and risk factors associated with ACL injury. However, there are drawbacks to in-vitro studies because it is difficult to reproduce certain natural, pathological, or degenerative situations.[18] Many experimental approaches omit multiple factors related to ACL injury such as muscle activation patterns, ankle and hip measurements, and knee joint geometry.[18] Omitting these measurements in a study approach does not represent the complexity of the knee joint during movement and therefore the mechanisms and risk factors contributing to injury cannot be completely understood. Ali and Rhoui[18] believe that experimental studies are too narrowly focused and that they lack standardization. They suggest that the ultimate way to understand the many variables that affect the ACL is to create an approach that simultaneously captures the interactions of multiple forces, risk factors, and other parameters that may contribute to non-contact ACL injury. The only difficulty is finding a concise technique to measure the combination of variables associated with injury to the ACL.

Prevention of ACL Injury

Although a large amount of information exists on how to treat and reconstruct an injured ACL, minimal information exists on exactly how to prevent ACL rupture from occurring. The multiple factors associated with ACL tears make it difficult to design a prevention program specific to all the needs of the individual. Current literature on prevention programs is abundant but does not come to a consensus because of our inability to specify the exact causes of ACL injury. Prevention programs focus on the biomechanical and neuromuscular components and encompass many different training regimens such as resistance training, plyometric training, balance training, core strengthening etc. Myer et al[15] reported that prevention programs should include multiple protocols focusing on neuromuscular training, core strengthening, resistance training, proprioceptive and balance training, and agility training to decrease the risk of ACL injury and improve athletic performance.

Biomechanical training. Bee-Oh Lim et al[1] observed high school female basketball players have higher knee flexion angles, greater interknee distances, lower hamstrings-to-quadriceps ratio, and lower maximum knee extension torques after participating in an eight week sports injury prevention training program. The purpose of the study was to focus on the effectiveness of a sports prevention training program to increase muscle strength, increase flexibility, and improve biomechanical properties related to ACL injury in high school female basketball players. They evaluated the subjects by using three-dimensional motion analysis, force plate, and EMG data during the landing phase of a rebound jump task measuring jump height, maximum knee flexion angle, minimum interknee distance, maximum knee internal rotation angle, maximum knee extension moment, maximum knee valgus moment, and hamstrings-to-quadriceps ratio. The 8-week protocol consisted of a warm-up, stretching, strengthening exercises, plyometric exercises, agility exercises, and alternative exercise-warm down exercises. The results indicated a training effect in all strength parameters and knee flexion when compared to a control group and strength increased significantly from pre-test to post-test in the experimental group. Also, the experimental group showed significant changes in the major risk factors measured in the study when compared to the control group and from pre-test to post-test. The mean knee flexion angle significantly increased from 92.66° to 94.27° and the mean knee distance increased from 17.56 cm to 20.81. The mean hamstrings-to-quadriceps ratio decreased from 75.09% to 67.97% and the mean maximum knee extension torque decreased from 236.96 N·m to 192.18 N·m.[1] The prevention program used during the study concurs with Myer et al[15], the idea that multiple protocols must be implemented to address all the different risk factors associated with ACL ruptures.

Brain-behavior relationship and motor learning. Overall behavioral changes are evident after participating in the various exercises within the injury prevention program. However, evidence is lacking whether the changes are due to peripheral adaptations, central adaptations, or a combination of the two.[21] Peripheral adaptations are changes in the muscular tissue itself whereas central adaptations are changes in the motor programming of the central nervous system.[21] Powers and Fisher[21] suggest that neuroplastic changes occur in the brain and are associated to the changes in behavior following an ACL injury-prevention training program. They conducted a 10-week pilot study comparing results from a strength training program and a skill-acquisition program, where the subjects were instructed on proper landing technique. They observed that skill-acquisition training is superior to strength training in eliciting correct landing techniques. Changes in behavior immediately after skill-acquisition training were retained when rechecked six months after training and increased use of hip extensors immediately after and 6 months after suggests decreased corticomotor excitability of the gluteus maximus. All these changes suggest that motor learning is occurring during the skill-acquisition training whereas fewer changes are occurring during strength training; hence the neuroplastic changes may underlie the behavioral changes following participation in ACL prevention programs. A specific type of motor learning may also play a part in the neuroplastic changes in the brain during ACL prevention programs especially those focused on the neuromuscular characteristics. Two ways of motor learning are explicit learning and implicit learning. Explicit learning is provided by an external source and the other type is implicit learning where individuals learn from themselves. Implicit motor learning styles should be implemented during ACL prevention programs versus explicit styles because implicit learning increases mirror neuron activation which enhances awareness during body movement.[22] If an individual has increased body awareness he or she is less likely to experience injury during high risk movements.

Neuromuscular training programs. Neuromuscular prevention programs are the most common form of prevention because they focus on improving body awareness and correcting detrimental biomechanical characteristics to reduce the risk of injury to the ACL. Along with decreasing the risk of ACL injury, neuromuscular prevention programs can improve performance in speed, agility, and power. Myer et al[14] observed a 92% increase in their subjects' 1 RM squat and 20% increase during bench press as well as lower 9.1 m sprint times, increased their distance for single-leg hop tests in both legs, and their double leg vertical jump measurements were higher following a 6-week comprehensive neuromuscular training program which included plyometric and movement training, core strengthening, balance training, resistance training, and interval speed training.

Kinematics and kinetics of jumping tasks. Myer et al[14] also observed biomechanical changes along with improvements in performance. Subjects had an average decrease of 28% (60.4 ± 5.5 N-m to 43.4 ± 3.3 N-m; $p < 0.001$) in right knee internal valgus torque, a 38% (34.0 ± 2.8 N-m to 21.1 ± 1.7 N-m; $p < 0.001$) decrease in their knee internal varus torque, and increased flexion-extension range of motion (71.9° ± 1.48° to 76.9° ± 1.48° $p < 0.001$ for the right knee and 71.3° ± 1.58° to 77.3° ± 1.48° $p < 0.001$) for the left knee during the landing phase of a box jump. Chappell and Limpisvasti[16] produced similar results when assessing the effects of a different 6-week neuromuscular training program focusing on plyometric training and core strengthening.

They noticed a decrease in dynamic knee valgus moment during the stance phase of a stop jump task and an increase in initial knee flexion and maximum knee flexion angles during the stance phase of drop jump tasks, which are three biomechanical factors relating to ACL damage. The subjects' performance values increased for vertical jump and both single-legged hop tests. These two studies[14,16] provide sufficient evidence that neuromuscular training programs reduce the biomechanical risks related to ACL injury and improve athletic performance by focusing on several aspects such as core strengthening, plyometric training, and agility training.

Trunk and hip control. Other common neuromuscular training programs center their focus on trunk and hip control to decrease the risk of injury because of weak hip musculature and poor control of the trunk. Myer et al[13] provide a progressive neuromuscular training program targeting trunk and hip control to improve core stability and decrease knee abduction by strengthening the hip musculature to reduce the predisposition to ACL injury. The selected exercise progressions were based on biomechanical investigations that reported reductions in knee abduction loads and include lateral jumping, single-leg anterior, prone trunk stability, kneeling trunk stability, single-leg lateral, tuck jump, lunge, lunge jump, hamstring-specific, single-leg rotatory, lateral trunk, trunk flexion, and trunk extension. Each progression consists of five phases that increase in difficulty and specificity at each level and progression can only be achieved by mastering the exercises in the previous phase.

Age-specific prevention programs. Myer et al[13] discussed how a progressive neuromuscular training program should be implemented in a pubertal or pre-pubertal female population to help reduce the risk of ACL injury and decrease the disparity between genders; however research is lacking on an ideal time period of when to implement such prevention programs. They assumed by incorporating a neuromuscular training program at the adolescent and pre-adolescent phases, females can improve lower extremity strength, power, single-leg balance, and overall knee joint biomechanics during biomechanics which will reduce the risk of injury by teaching correct knee joint biomechanics. The problem with a progressive neuromuscular training program is that children under the age of 12 may not be able to complete those exercises because they may be too difficult.[23] In order to reap the benefits of a neuromuscular training program the program should be age-specific and progressions should be made according to individually ability to complete the task. DiStefano et al[23] recognized that changes in biomechanical factors did vary greatly between using a traditional prevention program versus a pediatric program. The only significant finding was a decrease in knee external rotation at initial ground contact in the group who participated in the pediatric program.

The idea of when to implement neuromuscular prevention programs is controversial throughout the literature. Some researchers suggest that adolescent and pre-adolescent females should be exposed to a neuromuscular training program because younger populations are more efficient in motor learning while others question the logic of implementing such a comprehensive program at a young age. Myer et al[24] conclude that implementing an integrative neuromuscular training program during pre-adolescence enhances overall health and sport-related fitness as well as decreases the child's inherent risk of injury during adolescence and later stages of life. Although the concept is controversial, the logic behind providing a neuromuscular training program to preadolescents has many positive aspects; however, the protocol should be simple and specific so the child can attain the benefits from the neuromuscular training.

Summary

The higher rate of ACL injury in females is due to a combination of anatomical, biomechanical, and hormonal factors. Ligament dominance, leg dominance, quadriceps dominance, and trunk dominance are four main neuromuscular components that must be addressed in order to reduce the likelihood of injury in females. Almost every biomechanical risk factor associated with ACL injury can be categorized under one of these components. Although several limitations exist in ACL research, tools have been developed to evaluate injury risk focusing on biomechanical characteristics during high-risk movements. Without proper identification, detrimental injuries may occur to the knee joint and specifically the ACL. Injury to the ACL is highly debilitating and results in an expensive reconstructive procedure. In order to avoid the high costs of the popular method of reconstructive surgery, the focus needs to be turned to identifying individuals at high risk of injury and implementing a specific program to correct their biomechanical dysfunctions. Studies have shown that specific neuromuscular programs focusing on core strengthening, resistance training, plyometric training, trunk and hip control, proprioceptive and balance training, and agility training produce successful results in reducing known biomechanical risk factors. Motor learning occurs during neuromuscular training which improves the individual's overall body awareness. An individual with increased body awareness is less likely to be a victim of injury. Literature describes that body awareness decreases during puberty in females because anatomical, biomechanical, and hormonal changes occur during the growth spurt. This indicates that a neuromuscular prevention program may be more successful if implemented during the pre-adolescent and adolescent phases to reduce the risk of ACL injuries in females. However, literature is controversial and lacks consensus on when a neuromuscular prevention program should be implemented. Further research needs to be conducted to explain at what age a neuromuscular prevention program is most effective in diminishing the risk of ACL rupture in female athletes.

Methods

Problem Statement

The purpose of this study was to evaluate the biomechanical factors associated with ACL injury in Division II female collegiate athletes before, during (2 wks, 4 wks, 6 wks), and after an 8-week neuromuscular training program.

Research Questions

5. Did the LESS scores decrease after participating in an 8-week neuromuscular training program?
6. Was there significant improvement at 2 wks, 4 wks, 6 wks, and 8 wks?
7. Did knee valgus angles decrease after an 8-week neuromuscular training program?
8. Did knee flexion angles increase after an 8-week neuromuscular training program?

Experimental Design

A one-group design with repeated measures at five time points was used to guide data collection. The intervention was an 8-week neuromuscular training program and the independent variable was time (pre-training, 2 wks, 4 wks, 6 wks, and post-training). The dependent variables were the Landing Error Scoring System (LESS) score, knee valgus angle, and knee flexion angle.

Subjects

Healthy, Division II female collegiate athletes (volleyball and soccer) between the ages of 18 and 24 were recruited to participate in this study. Subjects were excluded from the study if they had experienced an ACL surgery in the past year, unless cleared by a physician or self-reported any neurologic, cardiovascular, or neuromuscular diseases.

Procedures

Subjects invited to participate in this study met at the Division II university to fill out a demographic form and sign the informed consent form. Body anthropometrics (height, weight, and body mass index) were measured for each subject. Also, during this time the researchers discussed the importance of adherence to the program.

The subjects were asked to wear spandex shorts and a sports bra or a spandex tank top. Anatomical markers will be placed on their bodies at the acromioclavicular joint, manubrium, greater trochanter, anterior superior iliac spine (ASIS) (R/L), lateral joint line of the knee, middle of the patella (R/L), tibial tuberosity (R/L), lateral malleolus, and ankle mortise (R/L). The subjects performed a drop-jump off a 30-cm high box to a distance of 50% of their height away from the box, onto the floor, then performed a maximal vertical jump upon landing. Subjects attended a familiarization session to familiarize them with the drop-jump. The subjects were evaluated on five separate occasions (pre-training, 2^{nd}, 4^{th}, 6^{th} week of training, and post-training). The LESS scoring system was used to evaluate the drop-jump. The drop-jump was recorded using two standard video cameras (Sony HDR-XR520V, San Diego, CA). One camera was placed to capture frontal plane motion and the other was placed to capture sagittal plane motion during the jump-landing procedure. The co-investigator evaluated each subject based on the LESS criteria. The LESS is a score based on the number of errors the subject performs during the jump-landing task. The LESS scoring system has a high reliability ($ICC_{2,1} = 0.91$, $ICC_{2,k} = 0.84$).[20] A higher score indicates poor landing technique whereas a lower score indicates a better landing technique. The co-investigator assessed 17 items relating to jump-landing technique (See Appendix E). Each jump recorded by the two video cameras was placed into Dartfish video software (Dartfish USA, Alpharetta, GA) so the co-investigator could assess the 17 different items and measure the amount of knee valgus and knee flexion. Knee flexion was measured using the video from the sagittal plane and anatomical markers at the greater trochanter, lateral joint line of the knee, and lateral malleolus. Knee valgus was measured using the video from the frontal plane and anatomical markers at the ASIS, center of patella, and ankle mortise. Subjects were re-evaluated after 2, 4, and 6 weeks into the neuromuscular training as well as a final post-training evaluation after the eighth week. The subjects' total scores for each time point were recorded for further statistical analysis to assess changes in biomechanical factors during the neuromuscular training program.

Participants performed a neuromuscular training protocol as described by Myer et al.[13] This neuromuscular program targets deficits in the trunk and hip. Subjects performed 13 exercise progressions each with five difficulty levels (phases) which help facilitate progress within the program. The exercise progressions (lateral jumping, single-leg anterior, prone trunk stability, kneeling trunk stability, single-leg lateral, tuck jump, lunge, lunge jump, hamstring-specific, single-leg rotatory, lateral trunk, trunk flexion, and trunk extension) within this neuromuscular training program are designed to improve the subjects' ability to control her trunk and improve core stability during dynamic movement. The difficulty of the task increases with each new phase of the progression. In order to progress to the next phase, the subject had to master the previous phase. Mastering the phase was based off of observation by the co-investigator on how easily the subject performed the maneuver and her technique. The research team provided feedback to the subjects about their technique but the co-investigator was the only individual determining when the subject moved to the next phase. The subjects participated in the neuromuscular training program three times per week over an 8-week period. All procedures were approved by the university's institutional review board and subjects provided written consent.

Statistical Analysis

Mean differences in LESS scores, knee valgus, and knee flexion were analyzed with a one-way repeated measures ANOVA over five time points. A paired samples t-test was used to compare pre- and post- test values of the LESS scores, knee flexion, and knee valgus. A Bonferroni adjustment for multiple comparisons was used to compare LESS scores, knee flexion angles, and knee valgus angles between each time point. An alpha level of 0.05 was used to test for significance. Statistical analyses were conducted with SPSS (IBM SPSS Statistics 20.0, Armonk, NY).

References

1. Lim BO, Lee YS, Kim JG, An KO, Yoo J, Kwon YH. Effects of sports injury prevention training on the biomechanical risk factors of anterior cruciate ligament

injury in high school female basketball players. *Am J Sports Med.* 2009; 37:1728-1734.

2. Arendt E and Dick R. Knee injury patterns among men and women in collegiate basketball and soccer – NCAA Data and Review of Literature. *Am J Sports Med.* 1995; 23:694-701.

3. Grindstaff TL, Hammill RR, Tuzson AE, Hertel J. Neuromuscular control training programs and noncontact anterior cruciate ligament injury rates in female athletes: numbers-needed-to-treat analysis. *J Athl Train*. 2006; 41:450-456.

4. Prentice WE. The knee and related structures. *Arnheim's Principles of Athletic Training—A Competency-Based Approac.* 12th ed. New York, NY: McGraw-Hill; 2006:629-632.

5. Hewett TE, Ford KR, Hoogenboom BJ, Myer GD. Understanding and preventing ACL injuries: current biomechanical and epidemiologic considerations - update 2010. *N Am J Sports Phys Ther*. 2010; 5:234-251.

6. Beutler AI, de la Motte SJ, Marshall SW, Padua DA, Boden BP. Muscle strength and qualitative jump-landing differences in male and female military cadets: The jump-ACL study. *J Sports Sci and Med*. 2009; 8:663-669.

7. Norcross MF, Blackburn JT, Goerger BM, Padua DA. The association between lower extremity energy absorption and biomechanical factors related to anterior cruciate ligament injury. *Clin Biomech*. 2010; 25:1031.

8. Myer G, Ford KR, Hewett TE. The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *J Electromyogr Kinesiol*. 2005; 15:181-189.

9. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc*. 2003; 35:1745-1750.

10. Eiling E, Bryant AL, Petersen W, Murphy A, Hohmann E. Effects of menstrual-cycle hormone fluctuations on musculotendinous stiffness and knee joint laxity. *Knee Surg Sports Traumatol Arthrosc*. 2007; 15:126–132.

11. Abt JP, Sell TC, Laudner KG, McCrory JL; Loucks TL, Berga SL, Lephart SM. Neuromuscular and biomechanical characteristics do not vary across the menstrual cycle. *Knee Surg Sports Traumatol Arthrosc*. 2007; 15:901–907.

12. Myer GD, Ford KR, Khoury J, Succop P, Hewett TE. Development and validation of a clinic-based prediction tool to identify female athletes at high risk for anterior cruciate ligament injury. *Am J Sports Med.* 2010; 38:2025-2033.

13. Myer GD, Chu DA, Brent JL, Hewett TE. Trunk and hip control neuromuscular training for the prevention of knee joint injury. *Clin Sports Med*. 2008; 27:425-448.

14. Myer D, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J. Strength Cond. Res*. 2005; 19:51–60.

15. Myer GD, Ford KR, Hewett TE. Methodological approaches and rationale for training to prevent anterior cruciate ligament injuries in female athletes. *Scand J Med Sci Sports*. 2004; 14:275-285.

16. Chappell JD and Limpisvasti O. Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *Am J Sports Med.* 2008; 36:1081-1086.

17. Anderson MK, Parr GP, Hall SJ. Knee conditions. *Foundations of Athletic Training: Prevention, Assessment, and Management.* 4th ed. Baltimore, MD: Lippincott Williams & Wilkins; 2009:579-580.

18. Ali N and Rouhi G. Barriers to predicting the mechanisms and risk factors of non-contact anterior cruciate ligament injury. *Open Bio Med Eng J*. 2010; 4:178-189.

19. Schultz SJ, Schmitz RJ, Nguyen A, et al. ACL research retreat v: an update on ACL injury risk and prevention, March 25-27, 2010, Greensboro, NC. *J Athl Train*. 2010; 45:499-508.

20. Padua DA, Marshall SW, Boling MC, Thigpen CA, Garrett Jr WE, Beutler AI. The Landing Error Scoring System (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics: The JUMP-ACL study. *Am J Sports Med.* 2009; 37:1996-2002.

21. Powers CM and Fisher B. Mechanisms underlying ACL injury-prevention training: the brain-behavior relationship. *J Athl Train.* 2010; 45:513–515.

22. Benjaminse A, Otten E. ACL injury prevention, more effective with a different way of motor learning?. *Knee Surg Sports Traumatol Arthrosc*. 2011; 19:622–627.

23. DiStefano LJ, Blackburn JT, Marshall SW, Guskiewicz KM, Garrett WE, Padua DA. Effects of an age-specific anterior cruciate ligament injury prevention program on lower extremity biomechanics in children. *Am J Sports Med*. 2011; 39:949-957.

24. Myer GD, Faigenbaum AD, Ford KR, Best TM, Bergeron MF, Hewett TE. When to initiate integrative neuromuscular training to reduce sports-related injuries and enhance health in youth?. *Curr Sports Med Rep.* 2011; 10:15

APPENDIX B. INSTITUTIONAL REVIEW BOARD APPROVAL

NDSU NORTH DAKOTA STATE UNIVERSITY

Institutional Review Board
Office of the Vice President for Research, Creative Activities and Technology Transfer
NDSU Dept. 4000
1735 NDSU Research Park Drive
Research 1, P.O. Box 6050
Fargo, ND 58108-6050

701.231.8995
Fax 701.231.8098
Federalwide Assurance #FWA00002439

January 10, 2013

Pamela Hansen
Department of Health, Nutrition & Exercise Sciences
BBFH

IRB Approval of Protocol **#HE13116**, "**Evaluation of Biomechanical Risk Factors in Collegiate Female Athletes Using the Landing Error Scoring System (LESS) After an 8-week Neuromuscular Training Program**"
Co-investigator(s) and research team: **Hillaree Leif, Charley Young**

Approval period: 1/10/13 to 1/9/2014 **Continuing Review Report Due: 12/1/2013**

Research site(s): **MSUM** Funding agency: **n/a**
Review Type: Expedited category # 4
IRB approval is based on original submission, with revised: protocol and demographic form (received 1/8/2013).

Additional approval is required:

- prior to implementation of any proposed changes to the protocol (*Protocol Amendment Request Form*).
- for continuation of the project beyond the approval period (*Continuing Review/Completion Report Form).* A reminder is typically sent two months prior to the expiration date; timely submission of the report is your responsibility. To avoid a lapse in approval, suspension of recruitment, and/or data collection, a report must be received, and the protocol reviewed and approved prior to the expiration date.

A report is required for:

- any research-related injuries, adverse events, or other unanticipated problems involving risks to participants or others within 72 hours of known occurrence (*Report of Unanticipated Problem or Serious Adverse Event Form*).
- any significant new findings that may affect risks to participants.
- closure of the project (*Continuing Review/Completion Report Form*).

Research records are subject to random or directed audits at any time to verify compliance with IRB regulations and NDSU policies.

Thank you for cooperating with NDSU IRB procedures, and best wishes for a successful study.

Sincerely,

Kristy Shirley

Kristy Shirley, CIP
Research Compliance Administrator

Last printed 1/10/2013 8:55:00 AM

NDSU is an EO/AA university.

APPENDIX C. DEMOGRAPHIC FORM

Trunk and Hip Neuromuscular Training Program Effects on the Female Athletes' Landing Mechanics
Demographic Form

For Investigator ONLY

ID Number _____________
BMI __________

Gender: _____ Male _____ Female

Height: _____Feet _____ Inches

Weight: ______lbs.

Academic Year in sport as of 2012:____Freshman _____Redshirt Freshman
_____Sophomore _____Junior _____ Senior _____5th Year

Age: _____18 _____19 _____20 _____21 _____22 _____23 _____Other

Dominant Leg: _____Right _____Left
(Dominant Leg is determined by which leg you prefer to kick a ball)

What sport do you participate in (circle one): Volleyball **or** Soccer

Have you had ACL injury or surgery? ____Yes _____No

Have you had any other knee surgery? ____Yes _____No

Do you have any cardiovascular, neuromuscular, and/or neurological diseases?

______Yes ______No

Previous Injuries:

Type of Injury ___________________________ _____Right _____Left

Surgery Required ____Yes _____No Date of Surgery ___/___/20___

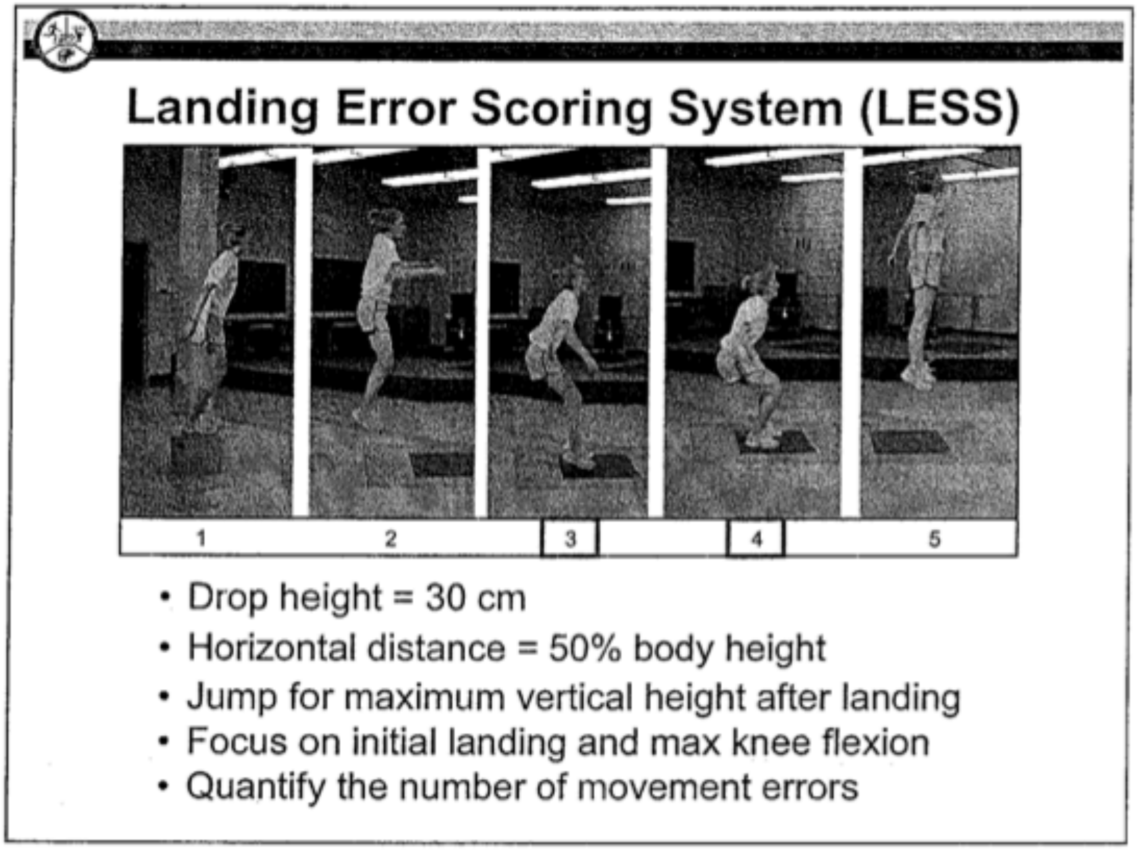
Type of Surgery ____

Type of Injury ___________________________ _____Right _____Left

Surgery Required ____Yes _____No Date of Surgery ___/___/20___

Type of Surgery ____

APPENDIX D. DROP JUMP



Adopted from Padua D (2011). *Identifying Modifiable Risk Factors for ACL Injury and Re-injury*.

APPENDIX E. LANDING ERROR SCORING SYSTEM (LESS)

1. **Knee Flexion @ Initial Contact: > 30 degrees**
   ____ Yes (0)
   ____ No (+1)

2. **Knee Valgus @ Initial Contact: Knees over midfoot**
   ____ Yes (0)
   ____ No (+1)

3. **Hip Flexion @ Initial Contact: Hips are flexed**
   ____ Yes (0)
   ____ No (+1)

4. **Trunk Flexion @ Initial Contact: Trunk is flexed**
   ____ Yes (0)
   ____ No (+1)

5. **Lateral Trunk Flexion @ Initial Contact: Trunk is vertical**
   ____ Sternum centered over hips (0)
   ____ Lateral deviation of sternum over hips (+1)

6. **Ankle Plantar Flexion @ Initial Contact: Toe to heel**
   ____ Yes (0)
   ____ No (+1)

7. **Foot Position @ Initial Contact: Toes > 30 of ER**
   ____ Yes (+1)
   ____ No (0)

8. **Foot Position @ Initial Contact: Toes > 30 of IR**
   ____ Yes (+1)
   ____ No (0)

9. **Stance Width @ Initial Contact:< Shoulder width**
   ____ Yes (+1)
   ____ No (0)

10. **Stance Width @ Initial Contact:> Shoulder width**
    ____ Yes (+1)
    ____ No (0)

11. **Initial Foot Contact: Symmetric**
    ____ Yes (+0)
    ____ No (+1)

12. **Knee Flexion Displacement: > 45 degrees**
    ____ Yes (0)
    ____ No (+1)

13. **Knee Valgus Displacement: ≥ great toe**
    ____ Yes (+1)
    ____ No (0)

14. **Hip Flexion Displacement: Hips flex more than at initial contact**
    ____ Yes (0)
    ____ No (1)

15. **Trunk Flexion Displacement: Trunk flexes more than at initial contact**
    ____ Yes (0)
    ____ No (1)

16. **Joint Displacement (Sagittal Plane)**
    ____ Soft (0)
    ____ Average (+1)
    ____ Stiff (+2)

17. **Overall Impression**
    ____ Excellent (0)
    ____ Average (+1)
    ____ Poor (+2)

Adopted from Padua D (2011). *Identifying Modifiable Risk Factors for ACL Injury and Re-injury.*

Table 3
Lateral jumping progression

Phase 1—Lateral jump and hold The athlete prepares for this exercise by standing with her feet close together and her knees slightly bent. The athlete should jump laterally over a line, keeping her knees bent and staying close to the line. When she lands on the opposite side, she should descend into a deep hold immediately.	
Phase 2—Lateral jumps The athlete prepares for this exercise by standing with her feet close together and knees slightly bent on one side of the line. The athlete should jump sideways over the line, keeping her knees bent and staying close to the line. When the athlete lands on the opposite side, she should redirect back to the initial position immediately. The athlete should repeat this sequence as quickly as she can while maintaining proper form. When teaching this exercise, encourage the athlete to achieve as many repetitions as possible in the allotted time by jumping close to the lines, shortening the ground contact time, and not using excessive height on the jumps. Do not allow the athlete to perform a double hop on the side of the line. Early in the training, the athlete may focus on the line; as her technique improves, encourage her to shift her visual focus away from the line to outside cues.	
Phase 3—Lateral hop and hold The athlete prepares for this exercise by standing on one foot with her knee slightly bent. The athlete should jump sideways over a line, keeping her knee bent and staying close to the line. When she lands on the opposite side, she should descend into a single-leg deep hold immediately.	
Phase 4—Lateral hops The athlete prepares for this exercise by standing on one leg with her knee slightly bent on one side of the line. The athlete should jump sideways over the line, keeping her knee bent and staying close to the line. When the athlete lands on the opposite side, she should redirect back to the initial position immediately. When teaching this exercise, encourage the athlete to achieve as many repetitions as possible in the allotted time by jumping close to the lines, shortening the ground contact time, and not using excessive height on the jumps. Do not allow the athlete to perform a double hop on the side of the line. Early in the training the athlete may focus on the line; as her technique improves encourage her to shift her visual focus away from the line to outside cues.	
Phases 5–10—Hops The athlete begins facing a quadrant pattern standing on a single limb with her support knee slightly bent. She will hop diagonally, landing in the opposite quadrant, maintaining forward stance, and holding the deep knee flexion landing for 3 seconds. The athlete then hops laterally into the side quadrant, again holding the landing. Next, the athlete will hop diagonally backward holding the landing. Finally, she hops laterally into the initial quadrant holding the landing. The athlete should repeat this figure 8 pattern for the required number of sets. Encourage the athlete to maintain balance during each landing, keeping her eyes up and her focus away from her feet.	

Table 4
Single-leg anterior progression

Phase 1—Step-hold The athlete starts by taking a quick step forward and continues by balancing in a deep hold position on the leg onto which she stepped.	
Phase 2—Jump–single-leg hold The athlete will begin this exercise in the athletic position. The athlete proceeds to jump forward, landing and balancing on one leg in a deep hold position.	
Phase 3—Hop hold Starting in a balanced position on one foot, the athlete hops forward, landing and balancing on one leg in a deep hold position.	
Phase 4—Hop-hop-hold The athlete hops forward twice quickly, landing and balancing on one leg in a deep hold position.	
Phase V—Crossover hop-hop-hold The athlete hops forward while alternating legs three times quickly, landing and balancing on one leg in a deep hold position.	

Table 5
Prone trunk stability progression

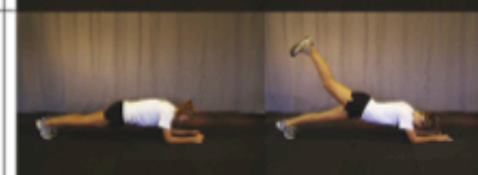
Phase 1—BOSU (round) toe touch swimmers The athlete begins in a prone position with her abdomen centered on the round side of the BOSU and her arms overhead and legs extended. The athlete reaches back with one arm to touch opposite foot and returns to the outstretched superman position.	
Phase 2—BOSU (round) swimmers with partner perturbations The athlete begins in prone position with abdomen centered on the round side of the BOSU and with her arms overhead and legs extended. The movement is initiated by elevating the opposite arm and leg, and held for 3 seconds. A partner will offer random perturbations by stepping on different sides of the BOSU during the exercise.	
Phase 3—Prone bridge (elbows and knees) hip extension opposed shoulder flexion The athlete begins in prone position with her elbows flexed and balanced on an Airex pad and knees on the ground. The movement is initiated by elevating the opposite arm and leg, and held for a single count and finished by returning to the original position.	
Phase 4—Prone bridge (elbows and toes) hip extension The athlete begins in prone position with elbows flexed and balanced on an Airex pad and toes on the ground. The movement is initiated by elevating the each leg individually, held for a single count, and finished by returning to the original position.	
Phase 5—Prone bridge (elbows and toes) hip extension opposite shoulder flexion The athlete begins in prone position with elbows flexed and balanced on an Airex pad and toes on the ground. The movement is initiated by elevating the opposite arm and leg, held for a single count, and finished by returning to the original position.	

Table 6
Kneeling trunk stability progression

Phase 1—BOSU (round) double-knee hold The athlete begins this exercise by balancing in a kneeling position with her knees on each side of the round side of the BOSU. The athlete will maintain this balanced position with the hips slightly flexed for the duration of the exercise.	
Phase 2—BOSU (round) single-knee hold The athlete begins this exercise by balancing in a kneeling position with one knee directly in the middle of the round side of the BOSU and the other knee extended out to the side. The athlete will maintain this balanced position with the hip slightly flexed for the duration of the exercise.	
Phase 3—Swiss ball bilateral kneel The athlete kneels and balances on Swiss ball with feet off the ground. A spotter should be available at all times in front of the athlete.	
Phase 4—Swiss ball bilateral kneel with partner perturbations The athlete kneels and balances on Swiss ball with her feet off of the ground. Once the athlete is stabilized, a partner can perturb the ball by kicking in unanticipated directions. A spotter should be available at all times in front of the athlete.	
Phase 5—Swiss ball bilateral kneel with lateral ball catch The athlete kneels and balances on Swiss ball with feet off the ground. A ball should be tossed back and forth with a partner to increase the difficulty of this exercise.	

Table 7
Single-leg lateral progression

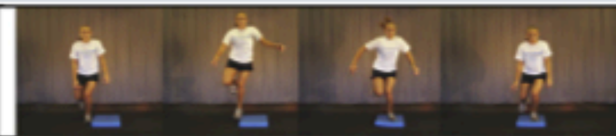
Phase 1—Single-leg lateral Airex hop hold Athlete starts on one side of the Airex pad and hops laterally onto the Airex. The athlete should maintain balance and hold the knee in a flexed position. The athlete then hops off the other side of the Airex onto the ground, maintains balance, and then repeats the exercise in the other direction.	
Phase 2—Single-leg lateral BOSU (round) hop hold Athlete starts on one side of the BOSU and hops laterally onto the BOSU. The athlete should maintain balance and hold the knee in a flexed position. The athlete then hops off the other side of the BOSU onto the ground, maintains balance, and then repeats the exercise in the other direction.	
Phase 3—Single-leg lateral BOSU (Round) hop hold with ball catch The athlete starts on one side of the BOSU and hops laterally onto the BOSU. The athlete should maintain balance and hold the knee in a flexed position. The athlete then hops off the other side of the BOSU onto the ground, maintains balance, and then repeats the exercise in the other direction. The athlete is challenged further by having to catch and return a ball upon each landing.	
Phase 4—Single-leg four-way BOSU (round) hop hold The athlete starts in a single-leg athletic position immediately behind the BOSU. The athlete hops forward onto the round side of the BOSU and lands in a balanced position. After achieving a balanced single leg stance on the BOSU, the athlete proceeds to hop off the BOSU laterally and assumes this same stance on the floor immediately next to the BOSU. The athlete then will continue to hop on and off the BOSU, achieving a balanced athletic position, in each of the four directions: forward, backward, lateral, and medial.	
Phase 5—Single-leg four-way BOSU (round) hop hold with ball catch The athlete starts in a single-leg athletic position immediately behind the BOSU. The athlete hops forward onto the round side of the BOSU and lands in a balanced position. After achieving a balanced single-leg stance on the BOSU, the athlete proceeds to hop off the BOSU laterally and assumes this same stance on the floor immediately next to the BOSU. The athlete then will continue to hop on and off the BOSU, achieving a balanced athletic position, in each of the four directions: forward, backward, lateral, and medial. A ball should be tossed back and forth with a partner upon landing to increase the difficulty of this exercise.	

Table 8
Tuck jump progression

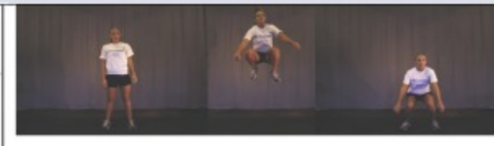
Phase 1—Single tuck jump soft landing The athlete starts in the athletic position with her feet shoulder width apart. The athlete initiates a vertical jump with a slight crouch downward while she extends her arms behind her. The athlete then swings her arms forward as she simultaneously jumps straight up and pulls her knees up as high as possible. At the highest point of the jump the athlete should be positioned in the air with her thighs parallel to the ground. On landing, the athlete should land softly, using a toe to midfoot rocker landing. The athlete should not continue this jump if she cannot control the high landing force or keep her knees aligned during landing. If the athlete is unable to raise the knees to the proper height, it may be valuable to instruct her to grasp the knees and then bring the thighs to horizontal.	
Phase 2—Double tuck jump Similar to the single tuck jump but with an additional jump performed immediately after the first jump. The athlete should focus on maintaining good form and minimizing time on the ground between jumps.	
Phase 3—Repeated tuck jump The athlete starts in the athletic position with her feet shoulder width apart. The athlete initiates a vertical jump with a slight crouch downward while she extends her arms behind her. The athlete then swings her arms forward as she simultaneously jumps straight up and pulls her knees up as high as possible. At the highest point of the jump, the athlete should be positioned in the air with her thighs parallel to the ground. When landing, the athlete immediately should begin the next tuck jump.	
Phase 4—Side-to-side tuck jumps The athlete starts in the athletic position with her feet shoulder width apart. The athlete initiates a vertical jump over a barrier with a slight crouch downward while she extends her arms behind her. The athlete then swings her arms forward as she simultaneously jumps straight up and pulls her knees up as high as possible. At the highest point of the jump, the athlete should be positioned in the air with her thighs parallel to the ground. When landing, the athlete immediately should begin the next tuck jump back to the other side of the barrier.	
Phase 5—Side-to-side reaction barrier tuck jumps The athlete starts in the athletic position with her feet shoulder width apart. The athlete initiates a vertical jump over a barrier with a slight crouch downward while she extends her arms behind her. The athlete then swings her arms forward as she simultaneously jumps straight up and pulls her knees up as high as possible. At the highest point of the jump, the athlete should be positioned in the air with her thighs parallel to the ground. When landing the athlete immediately should begin the next tuck jump. When prompted, the athlete should jump to the other side of the barrier without breaking rhythm.	

Table 9
Lunge progression

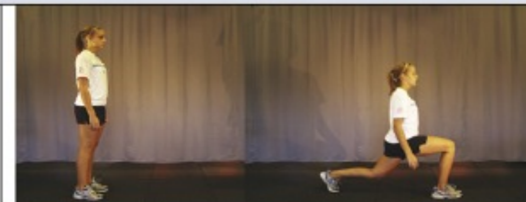
Phase 1—Front lunges The athlete begins by stepping forward from a standing position. The step should be exaggerated in length to the point that her front leg is positioned with the knee flexed to 90° and the lower leg completely vertical. The back leg should be as straight as possible and the torso upright. Emphasis should be placed on getting the hips as low as possible while maintaining the previously described body position. Driving off the front leg and returning to the original position complete the exercise.	
Phase 2—Walking lunges The athlete performs a lunge and instead of returning to the start position she steps through with the back limb and proceeds forward with a lunge on the opposite limb. Encourage the athlete to lunge her front limb far enough out so that her knee does not advance beyond her ankle during the exercise. An alternative coaching method is to instruct the athlete to attempt to maintain a constant low center of gravity and roll through the lunges. This increases the intensity of the exercise and attempts to mimic motions frequently occurring in sports.	
Phase 3—Walking lunges unilaterally weighted The athlete performs a lunge, and instead of returning to the start position, she steps through with the back limb and proceeds forward with a lunge on the opposite limb while holding a dumbbell in one hand. Encourage the athlete to lunge her front limb far enough out so that her knee does not advance beyond her ankle during the exercise. This exercise is repeated with the dumbbell in the opposite hand.	
Phase 4—Walking lunges with plate crossover The athlete performs a lunge, and instead of returning to the start position, she steps through with the back limb and proceeds forward with a lunge on the opposite limb while reaching with a weight plate to the open side of the body. Encourage the athlete to lunge her front limb far enough out so that her knee does not advance beyond her ankle during the exercise.	
Phase 5—Walking lunges with unilateral shoulder press The athlete performs a lunge, and instead of returning to the start position, she steps through with the back limb and proceeds forward with a lunge on the opposite limb while pressing a dumbbell above her head. The weight should move up and down with the same tempo and direction as the lunge. Encourage the athlete to lunge her front limb far enough out so that her knee does not advance beyond her ankle during the exercise.	

Table 10
Lunge jump progression

Phase 1—Lunge jumps The athlete starts in an extended stride position with the hips pushed forward, and the front knee positioned directly above the ankle and flexed to 90°. The back leg is fully extended at the hip and knee providing minimal support for the stance. The athlete should jump vertically off of the front support leg, maintaining the starting position during flight and landing. The jump is repeated as quickly as possible while still achieving maximum vertical height. To coach this jump, encourage the athlete to keep the back leg straight and use it only for balance support. The front leg obtains vertical power. Stance support percentages are approximately 80% for the front leg and 20% for the back.	
Phase 2—Scissor jumps The athlete starts in an extended stride position with the hips pushed forward, and the front knee positioned directly above the ankle and flexed to 90°. The back leg is fully extended at the hip and knee providing minimal support for the stance. The athlete should jump vertically off of the front support leg and switch the position of the legs while in flight. The jump is repeated as quickly as possible while still achieving maximum vertical height. The athlete will be jumping off alternate legs on each jump during this exercise.	
Phase 3—Lunge jumps unilaterally weighted The athlete starts in an extended stride position with her hips pushed forward, and the front knee positioned directly above the ankle and flexed to 90°. The back leg is extended fully at the hip and knee providing minimal support for the stance. The athlete should jump vertically off of the front support leg, maintaining the starting position during flight and landing. The jump is repeated as quickly as possible while still achieving maximum vertical height. To unilaterally weight this exercise, a dumbbell should be held in one hand. This exercise then is repeated with the dumbbell in the opposite hand.	
Phase 4—Scissor jumps unilaterally weighted The athlete starts in an extended stride position with the hips pushed forward, and the front knee positioned directly above the ankle and flexed to 90°. The back leg is extended fully at the hip and knee providing minimal support for the stance. The athlete should jump vertically off of the front support leg and switch the position of the legs while in flight. The jump is repeated as quickly as possible, while still achieving maximum vertical height. To unilaterally weight this exercise, a dumbbell should be held in one hand. The athlete will be jumping off alternate legs on each jump during this exercise. This exercise is repeated with the dumbbell in the opposite hand.	
Phase 5—Scissor jumps with ball swivel The athlete starts in an extended stride position with the hips pushed forward, and the front knee positioned directly above the ankle and flexed to 90°. The back leg is extended fully at the hip and knee providing minimal support for the stance. The athlete should jump vertically off of the front support leg and switch the position of the legs while in flight. The jump is repeated as quickly as possible while still achieving maximum vertical height. To unilaterally weight this exercise, a medicine ball should be swiveled to the open side of the body during each jump. The athlete will be jumping off alternate legs.	

Table 11
Hamstring-specific progression

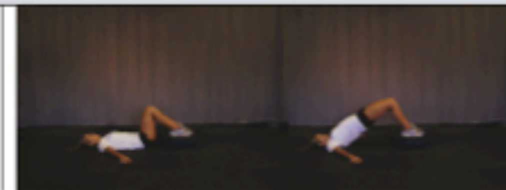
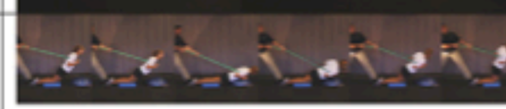
Phase 1—BOSU (flat) pelvic bridge The athlete lays supine with her hip and knees flexed and her feet planted on the flat side of the BOSU. The athlete then extends her hips and elevates her trunk off the ground to execute a pelvic bridge. This position should be held for 3 seconds before repeating the next repetition.	
Phase 2—BOSU (flat) single-leg pelvic bridge The athlete lays supine with her hip and knees flexed and a single foot planted on the flat side of the BOSU and the contralateral leg fully extended. The athlete then extends her hips and elevates her trunk off the ground to execute a pelvic bridge. This position should be held for 3 seconds before repeating the next repetition.	
Phase 3—BOSU (flat) single leg pelvic bridge The athlete lays supine with her hip and knees flexed and a single foot planted on the flat side of the BOSU and the contralateral leg fully extended holding a ball directly above her in her hands. The athlete then extends her hips and elevates her trunk off the ground to execute a pelvic bridge. This position should be held for 3 seconds before repeating the next repetition. A weight plate is positioned on the hips to add resistance.	
Phase 4—Supine Swiss ball hamstring curl The athlete lays supine with her hip and knees flexed with both heels planted on top of a Swiss ball. The athlete then extends her hips and elevates her trunk off the ground while pulling her heels in to her buttocks.	
Phase 5—Russian hamstring curl with lateral touch The athlete begins in a kneeling position with a partner providing foot support and torso support (with band assistance). The athlete extends at the knee to lower her torso toward the ground. Once touching the BOSU with her chest, the athlete swivels her trunk and returns to the original position. The coach should provide enough assistance so that the exercise can be performed without flexing at the hip.	

Table 12
Single-leg rotatory progression

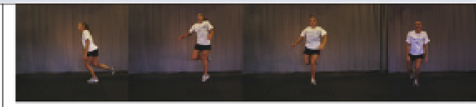
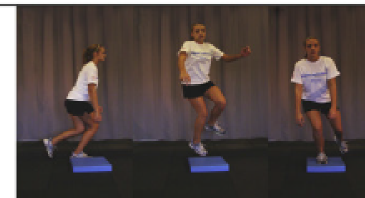
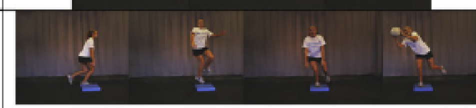
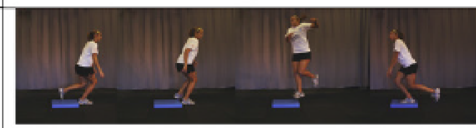
Phase 1—Single-leg 90° hop hold The starting position for this jump is with the athlete in a semicrouched position on the single limb being trained. The jump should focus on attaining maximum height while maintaining good form upon landing. During the flight phase, the athlete should rotate 90°. The landing occurs on the same leg and should be performed with deep knee flexion (to 90°). The landing should be held for a minimum of 3 seconds to be counted as a successful landing. Coach this jump with care to protect the athlete from injury. Start the athlete with a submaximal effort so she can experience the difficulty of the jump. Continue to increase the intensity of the jump as the athlete improves her ability to stick and hold the final landing. Have the athlete keep her focus away from her feet, to help prevent too much forward lean.	
Phase 2—Single-leg 90° Airex hop hold The starting position for this jump is with the athlete in a semicrouched position on the single limb being trained. The jump should focus on attaining maximum height while maintaining good form upon landing. During the flight phase, the athlete should rotate 90°. The landing occurs on the same leg and should be performed with deep knee flexion (to 90°). The landing should be held for a minimum of 3 seconds on an Airex pad to be counted as a successful landing. Coach this jump with care to protect the athlete from injury.	
Phase 3—Single-leg 90° hop-hold reaction ball catch The starting position for this jump is with the athlete in a semicrouched position on the single limb being trained. The jump should focus on attaining maximum height while maintaining good form upon landing. During the flight phase, the athlete should rotate 90°. The landing occurs on the same leg and should be performed with deep knee flexion (to 90°). The landing should be held for a minimum of 3 seconds on an Airex pad to be counted as a successful landing. Upon landing a ball will be passed back and forth with the athlete to increase the difficulty of a successful landing.	
Phase 4—Single-leg 180° Airex hop hold The starting position for this jump is with the athlete in a semicrouched position on the single limb being trained. The jump should focus on attaining maximum height while maintaining good form upon landing. During the flight phase, the athlete should rotate 180°. The landing occurs on the same leg and should be performed with deep knee flexion (to 90°). The landing should be held for a minimum of 3 seconds on an Airex pad to be counted as a successful landing.	
Phase 5—Single-leg 180° Airex hop-hold reaction ball catch The starting position for this jump is with the athlete in a semicrouched position on the single limb being trained. The jump should focus on attaining maximum height while maintaining good form upon landing. During the flight phase, the athlete should rotate 180°. The landing occurs on the same leg and should be performed with deep knee flexion (to 90°). The landing should be held for a minimum of 3 seconds on an Airex pad to be counted as a successful landing. Upon landing, a ball will be passed back and forth with the athlete to increase the difficulty of a successful landing.	

Table 13
Lateral trunk progression

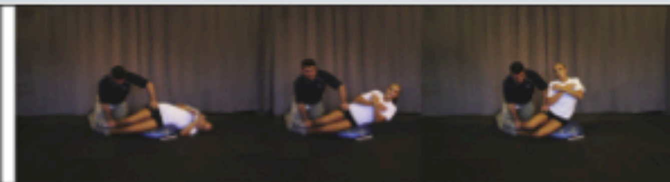
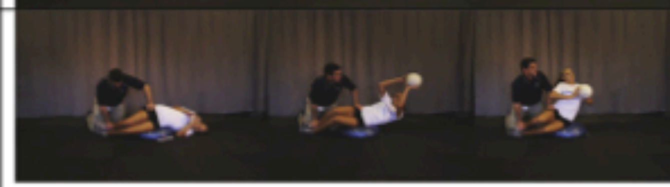
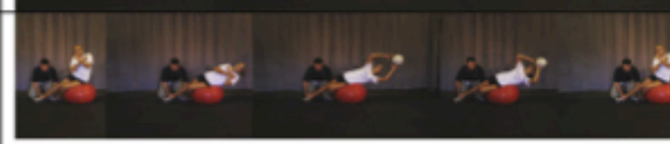
Phase 1—BOSU (round) lateral crunch The athlete starts lying on her side with her hip located in the center of the round side of the BOSU. The athlete's feet and legs must be anchored during this exercise by the trainer or a stationary object. The athlete will proceed to bend laterally at the waist back and forth for the prescribed repetitions.	
Phase 2—Box lateral crunch Athlete starts in a supine position on a plyo box with arms placed on the back of the head. The athlete flexes her trunk simultaneously with hip flexion. As the trunk and hip are maximally flexed, the athlete rotates at the trunk touching each elbow to the opposite knee.	
Phase 3—BOSU (round) lateral crunch with ball catch Athlete starts lying on side with hip located top of the round side of a BOSU. The athlete's feet and legs must be anchored during this exercise by the trainer or a stationary object. The athlete will proceed to bend laterally at the waist back and forth for the prescribed repetitions. A ball should be tossed back and forth with a partner to increase the difficulty of this exercise.	
Phase 4—Swiss ball lateral crunch Athlete starts lying on side with hip located top of a Swiss ball. The athlete's feet and legs must be anchored during this exercise by the trainer or a stationary object. The athlete will proceed to bend laterally at the waist back and forth for the prescribed repetitions.	
Phase 5—Swiss ball lateral crunch with ball catch Athlete starts lying on side with hip located top of a Swiss ball. The athlete's feet and legs must be anchored during this exercise by the trainer or a stationary object. The athlete will proceed to bend laterally at the waist back and forth for the prescribed repetitions. A ball should be tossed back and forth with a partner to increase the difficulty of this exercise.	

Table 14
Trunk flexion progression

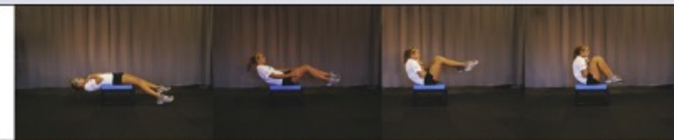
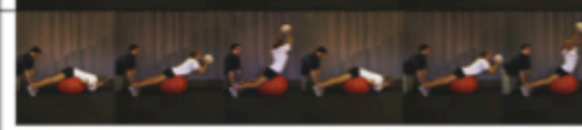
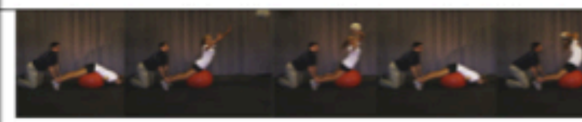
Phase 1—Box double crunch The athlete starts out supine on a plyometric box or similar object and flexes her trunk simultaneous with hip flexion.	
Phase 2—Box swivel double crunch Athlete starts in a supine position on a plyo box with arms placed across chest. The athlete flexes her trunk simultaneous with hip flexion. As the trunk and hip are maximally flexed, the athlete rotates at the trunk, touching each elbow to the opposite knee.	
Phase 3—BOSU (round) swivel ball touches (feet up) Athlete starts sitting on the round side of a BOSU holding a medicine ball. The athlete will proceed to swivel at the trunk to touch the medicine ball to the floor for each repetition.	
Phase 4—BOSU (round) double crunch Athlete starts sitting on the round side of a BOSU. The athlete flexes her trunk simultaneous with hip flexion.	
Phase 5—BOSU (round) swivel double crunch Athlete starts sitting on the round side of a BOSU. The athlete flexes her trunk simultaneous with hip flexion. As the trunk and hip are maximally flexed, the athlete rotates at the trunk touching each elbow to the opposite knee.	

Table 15
Trunk extension progression

Phase 1—Swiss ball back hyperextensions The athlete begins in a prone position on the Swiss ball, with her hips centered on top of the Swiss ball and a partner anchoring her feet to the floor. The movement is initiated by extending her hips and lower back to bring the athlete into a position of slight hyperextension. The position should be maintained for a short pause and then returned to the flexed position.	
Phase 2—Swiss ball back hyperextensions with ball reach The athlete begins in a prone position on the Swiss ball with her hips centered on top of the Swiss ball and a partner anchoring her feet to the floor. The movement is initiated by extending hips and lower back to bring the athlete into a position of slight hyperextension. While performing this motion the athlete will also extend and return a medicine ball from the chest to full shoulder and elbow extension and back to the chest.	
Phase 3—Swiss ball hyperextensions with back fly The athlete begins in a prone position on the Swiss ball with her hips centered on top of the Swiss ball and a partner anchoring her feet to the floor. The movement is initiated by extending hips and lower back to bring the athlete into a position of slight hyperextension. The position should be maintained while the athlete brings dumbbells out to the side similar to a back fly exercise.	
Phase 4—Swiss ball hyperextensions with ball reach lateral The athlete begins in a prone position on the Swiss ball with her hips centered on top of the Swiss ball and a partner anchoring her feet to the floor. The movement is initiated by extending hips and lower back to bring the athlete into a position of slight hyperextension. The position should be maintained while the athlete brings a medicine ball above her head and slightly to the side.	
Phase 5—Swiss ball hyperextensions with lateral ball catch The athlete begins in a prone position on the Swiss ball with her hips centered on top of the Swiss ball and a partner anchoring her feet to the floor. The movement is initiated by extending hips and lower back to bring the athlete into a position of slight hyperextension. The position should be maintained while the athlete brings a medicine ball above her head and slightly to the side. A ball should be tossed back and forth with a partner to increase the difficulty of this exercise.	

Adopted from Myer GD, Chu DA, Brent JL, Hewett TE. Trunk and hip control neuromuscular training for the prevention of knee joint injury. *Clin Sports Med*. 2008; 27:425-448.